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DEMAND RESPONSE PARTICIPATION IN DIFFERENT MARKETS IN EUROPE

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ABSTRACT

Marta de España Zaforteza: DEMAND RESPONSE PARTICIPATION IN DIFFERENT MARKETS IN EUROPE

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Maintain a reliable and secure electricity supply while carrying out the goal of decarbonisation that is intended at a European level by 2050 at the same time as the mass integration of renewable energy is a challenge that must be faced nowadays. Reliable and secure electricity supply is achieved with the perfect balance between generation and demand in real time. The intermittency from renewable energy sources generation does not help to maintain this balance, so it is necessary to look for alternatives that improve it. This paper analyzes how, thanks to technology development, demand response could participate in this balance and improve the reliability, security and quality of supply. Through literature review, other benefits that DR deployment could provide to stakeholders are also presented.

Many barriers and challenges explain the lack of its implementation among Europe, these are also mentioned. The main challenge is the lack of a common legislative framework in Europe. "Clean Package" which includes a Directive and Regulation of the internal market for electricity, consider fundamental aspects but require some changes on the current national regulations regarding the electricity markets.

Criteria are established to analyze the state of deployment and participation of DR in five European countries (Finland, Spain, United Kingdom, France and The Netherlands). After seeing the degree of development, pilot and demonstrations projects in these countries, it is observed that there are wide differences between the Member States, mainly due to national regulatory barriers.

Keywords: Ancillary Services, Demand Response, Electricity markets, European energy policies, Flexibility

The originality of this thesis has been checked using the Turnitin OriginalityCheck service.

PREFACE

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Tampere, 27 June 2019

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LIST OF SYMBOLS AND ABBREVIATIONS

aFRR	Automatic frequency restoration reserve
ACER	Agency for the Cooperation of Energy Regulators
AI	Artificial Intelligence
AMI	Advanced Metering Infrastructure
BACS	Building Automation and Control System
BEMS	Building Energy Management Systems
BoB	Block of Buildings
BMS	Building Management System
BRP	Balancing responsible party
BSP	Balancing service provider
C&I	Commercial and Industrial
CHP	Combined Heat and Power
CNMC	<i>“Comisión Nacional de los Mercados y la Competencia”</i>
CPP	Critical Peak Pricing
DER	Distributed Energy Resources
DG	Distributed Generation
DR	Demand Response
DSBR	Demand Side Balancing Reserve
DSM	Demand Side Management
DSO	Distribution System Operator
EC	European Commission
EDF	Electricité De France
EED	Energy Efficiency Directive
EMA	Electricity Market Act
EMS	Energy management system
ENTSO-E	European Network of Transmission System Operators for Electricity
ESCO	Energy Services Companies
EPEX	European Power Exchange
ERDF	European Regional Development Fund
EU	European Union
EV	Electric Vehicle
FCR	Frequency Containment Reserves (primary reserve of power)
GEMA	Gas and Electricity Market Authority
GHG	Greenhouse Gas
GLEB	Guideline on Electricity Balancing
HAN	Home Area Network
HEMS	Home Energy Management System
HVAC	Heat Ventilation Air Conditioning
IBP	Incentive-Based Programs
ICT	Information and Communication Technology
IoT	Internet of Things
IT	Information Technology
JRC	Joint Research Centre
MARI	Manually Activated Reserves Initiative
mFRR	Manually Frequency Restoration Reserve
NAN	Neighbourhood Area Network
NEBEF	Notification d’Échange de Blocs d’Effacement
NEEAP	National Energy Efficiency Action Plan
NIS	Network and Information Systems

Ofgem	Office of Gas and Electricity Markets
OMIE	<i>“Operador del Mercado Ibérico”</i>
PICASSO	Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation
PBP	Price-Based Programs
PEV	Plug-in Electric Vehicle
PLC	Power line carrier
PV	Photovoltaic
P2P	Peer to Peer
REE	Red Eléctrica de España
RES	Renewable Energy Sources
RIIO	Reserves=Incentives+Innovation+Outputs
RR	Replacement Reserves
RTE	Réseau de Transport d’Électricité
RTP	Real Time Pricing
SBR	Supplemental Balancing Reserve
SCADA	Supervisory Control and Data Acquisition
STOR	Short Term Operating Reserve
TA	Transitional Arrangements
TERRE	Trans European Replacement Reserves Exchange
ToU	Time of Use
TSO	Transmission System Operator
TPI	Third Parties Intermediaries
UK	United Kingdom
USA	United States of America
VPP	Virtual Power Plant
WAN	Wide Area Network
WRI	World Resource Institute

1. INTRODUCTION

We are at the beginning of an energy transition. The European Council in 2007 adopted ambitious energy and climate change objectives for 2020 and 2030 [1]. European Council has also given a long-term commitment to the decarbonisation path with a target for the European Union and other industrialized countries to cut their domestic greenhouse gas (GHG) emissions to 80% below 1990 levels by 2050 [2]. Moreover, the European Parliament has continued supporting these goals by replacing the large thermal centralized generators to a sustainable and competitive electricity market with renewable energies integration.

Due to the integration of renewable energies as wind and solar power to the electrical system the concept of Distributed Generation (DG) has arisen. DG is defined as generation of electricity on a small scale and close to consumer. Literature and researchers have been for years discussing the benefits of this new form of generation from the point of view of efficiency, flexibility, interconnection between distribution networks, emissions levels and investments for installation and maintenance and operation costs.

Consequently, companies in the electricity sector should be prepared for the entry of new products and services that allow them to adapt to new times. New times mean changes in the distribution and transmission networks, sources of energy and the increasing small scale electricity generation. Much of these changes expected to include the customer to the chain because of on-site generation, self-consumption thanks to advances in technology and automation. From the introduction of the customer to the electricity chain arise the concept of Demand Response (DR) which is analysed along this document. Consumer is expected to produce energy, in this context, consumer happens to be called “prosumer”.

It is evident that the energy system is on the verge of a deep and far-reaching transformation. In order to that transformation to be possible, and as energy sector is highly regulated as a consequence of the existence of natural monopolies and because of its strategic nature for the countries, regulation must evolve at the same pace. Legislative framework, at European Union and national level, must evolve to facilitate this change and ensure the best protection of the interests of the stakeholders. Nevertheless, the

existing strategy is currently unlikely to achieve all the 2020 targets, and it could also be inadequate to the medium and long-term challenges. The Energy Union, promoted in 2015 by the European Commission, aims to guarantee security of supply and move towards a competitive single market. For that reason, new platforms and projects for the exchange of balancing energy across Europe are also presented in this document [3].

Recent reforms in all major countries have as main objective to adapt the electrical system to achieve the environmental objectives for 2030 and 2050 and to meet GHG emission reduction targets set by the COP 21 Paris Climate Accord. For this purpose, a reform proposal approved recently wants to enhance the role of the consumer in the market, facilitate the integration of renewable and increase the effective interconnection between national power systems [4].

Applied to the wholesale electricity market, the philosophy is based on more collaborative consumers, trying to reduce the distance between the retail and wholesale markets. So that, thanks to new technologies, smart meters and continuous communications, the consumer can decide its consumption and increase their efficiency by benefiting from lower prices during certain periods. To reach that, all consumers, domestic and industrial, must be able to have access to the market to be able to negotiate with their demand and with their self-produced energy. On the demand side, new participants will appear in the electricity system chain being the aggregation the protagonist of this change.

When a determined volume of distributed generation is implanted, as penetration of intermittent renewable generation, which are variable according to the weather conditions and sometimes different from forecasted, changes in the demand curve will arise and it is essential to anticipate to them. This instability created by self-consumption mechanisms will need to be regulated having in mind the awareness of balance fluctuations and considerate them as an opportunity in the electricity market. Smart grids with flexible generation resources, high data management, and growth of interconnection between power systems and regions and electricity storage are recent options to balance the power system.

To achieve the European objectives and make all the above feasible, it is necessary to increase the interconnections between networks and harmonize electricity markets around Europe, make loads capacity available to wholesale markets and bet on storage systems. The aim of the electricity supply is to provide the consumer demand with solidly available (security of supply) and satisfactory (quality of supply) electrical energy

(with adequate frequency and voltage), on as low full costs as possible. Also, the goal is to balance the system in the most efficient way which sometimes it means reduction of demand fluctuation, and sometimes is needed to increase consumption to compensate production fluctuations. In some countries, it has already started; this little amount of distributed resources begins to affect the network. All that leads to the importance of knowing how the participation of the independent aggregation is regulated and which the expectations for next years are [5]. Independent aggregation is defined as the aggregation of loads of consumers with capability to reduce energy and/or shift loads on short notice sold in the market as a single resource by the aggregator [6].

From all mentioned appears Demand Side Management (DSM) and part of it, Demand Response (DR). DR is seen as a solution which considers the consumer participation for uncertain and fluctuating power supply, increase efficiency, reduce GHG emissions and more benefits explained in this master thesis; this are some reasons why it has been recently included in the European Commission's legislative proposals on electricity market. Currently, the main obstacle is the lack of harmonized standards defining roles, responsibilities of DR stakeholders between Member States complex power systems.

Moreover, advances in IT, control, monitoring technology and forecasting capabilities have made DR a viable, and potentially attractive option to increase power system flexibility [7]. DR is essential to achieve an efficient, reliable and sustainable electrical system at a reasonable price from both, high-voltage grid and low voltage grid thorough "prosumption" [8]. *Generation-follows-demand* perspective is increasingly replaced by a *demand-follows-generation*.

Finally, DR paradigm can be summarized in the figure below. Some milestones have already been reached to achieve the energy policy targets of security, affordability and sustainability. Demand Response allow consumer to have access to markets, participate in grid balance and be in contact with retailers. This is possible by combining six changes which are already done or are easy to achieve: change the concept of balancing instead of matching supply and demand, include bi-directional electricity flow, integrate consumer to the chain, take advantage of improving communications to allow collaboration among the parts involved , value flexibility apart from energy and integrate distributed generation.

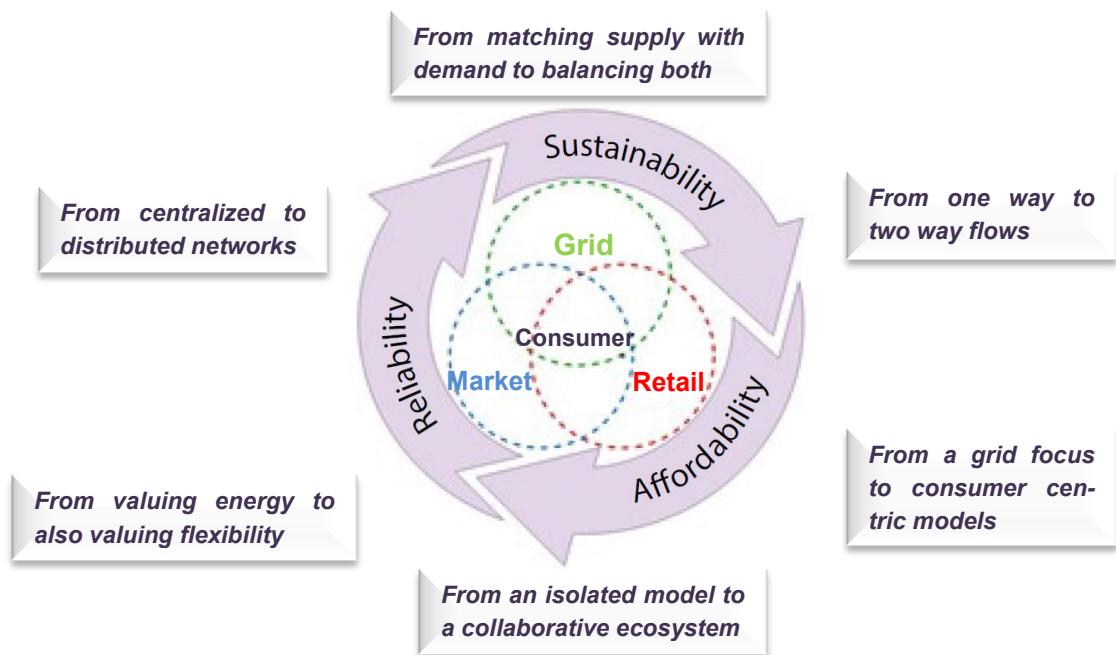


Figure 1. Demand Response paradigm [61].

1.1 Objective and scope of the thesis

The main objectives and research questions formed for this thesis are:

- How is the legislative framework of DR across Europe?
- How the introduction of DR affects the reliability of the power grid?
- Are DR benefits and costs uncertain thereby DR is slowly integrated within competitive electricity markets?
- How DR could interact optimally with energy efficient and climate change actions? Which are the barriers and challenges tackled at the moment?
- Can DR be used for Ancillary Services?
- How is the current and future overview of the participation of DR in Europe, particularly in five Member States (Finland, Spain, UK, France and the Netherlands)

The study is done focusing on the European power systems. The objective of this master's thesis is to give a current overview of DR in Europe. Additionally, the aim is to evaluate the current status of DR globally and more deeply in some European countries like Finland, Spain, United Kingdom (UK), France and The Netherlands.

Innovation and regulation must work closely together and in the same pace to DR deployment. Besides, the requirements for its development and how advances are carried out with some demonstrations and pilot projects around the world. To evaluate the advantages and disadvantages of DR, the market and stakeholders' analysis are also presented therein.

1.2 Structure of the work

This master thesis is focused on DR participation across Europe. The work is organized as follows: throughout chapters 2 and 3, DR is defined and classified according to the different programs existing and consumer's response types. Once provided some background on DR in chapter 4 some main contributions with respect to existing studies are done as well as the current legislative framework for DR in Europe. After mentioning the deployment of DR and its trend, chapter 5 assesses the roles, expectations and potential benefits from the viewpoint of different relevant stakeholders to understand their importance relating to the deployment of DR as well as the challenges and barriers of its progress.

Finally, chapters 6 and 7 are focused in the target countries, with in-depth case studies of, Finland, Spain, the UK, France and the Netherlands. Chapter 6 explains the criteria considered for the analysis of the target countries among chapter 7. The thesis will finish with some conclusions about the current status of DR and the issues that still need to be addressed.

The methodology employed is mainly based on desk research techniques via literature review. Throughout the thesis, a special emphasis on providing useful references on the different topics will be made. Some limitations to consider are the continuous changes and evolution of conditions for DR and the disaggregated and heterogeneous contexts and markets from technical to legislative point of views.

2. GENERAL OVERVIEW OF DR

To have a better understand of DR, first is going to be explained how electricity markets and operations are organised and carried out and after that how is DR included to those electricity markets.

2.1 DR in electricity markets around Europe

Electricity industry is a dynamic and highly complex system because of rapid and unexpected changes due to transmission and distribution line outages, production variations and sudden load changes. Its economic properties such as the no-direct-storability, hardly replaceable, inelastic demand and some technical peculiarities make electricity a unique commodity.

Maintaining a reliable and secure operation is essential on the power system. Secure operation requires a perfect balance between supply and demand in real time, this dynamic equilibrium is carried out with the values of frequency, voltage, and currents [9]. Particularly, perfect balance is achieved maintaining stable frequency: 50 Hz in Europe and most of the countries across the world and 60 Hz in some other places like United States of America (USA).

On the one hand, the main challenge for operation is to consider that electric power is not economically storable at great scale and generation costs are diverse because of the generation units' classification. Once electricity is generated, it flows to customers by wires over a transmission and distribution networks.

On the other hand, inelastic demand curve is caused by the lack of agreements between wholesale markets and retailers. In most situations, consumers do not apperceive the real cost of reliable electricity supply and do not receive enough incentives to adapt their consumption in every moment.

Electric power systems around the world have similar structure and configuration. In most countries, wholesale electricity market design has evolved towards the use of short-term marginal costs as the optimal economic signal for energy trading. In liberalized markets, retailers and producers can also set up bilateral contracts for electricity supply, where only a small part of the electricity demand is traded in real-time. Capacity markets, not used in all electricity markets, are also utilized for long term procurement

of electricity provision by all market parties. Otherwise in non-liberalized market, the system operator solely operates its plants centrally to meet electricity demand, assigning the right unit at the right times [10].

Markets for power have been developed over the years due to liberalization of power industries. Most of electricity markets are divided into three categories: product market, control reserve exchange and balancing energy [11]. Successive electricity markets with different time scales (forward, capacity, day-ahead, intraday, and set of balancing markets) have their own rules for transactions between generation and load parties [12].

Day-ahead electricity market operates a day in advance of the physical delivery of power. Usually, that market is the most important in terms of trading volume. In this environment, deadline for bids, normally, is one day in advance from the delivery of power, which is organized for each hour of the day. After that, a two-sided auction, producing (selling) and consuming (buying) agents, submit a set of price-quantity curves (bids) and accordingly results the generation decisions for the next day.

Generally, the Power Exchange manages the market clearing while in some countries also matches demand and supply. Power exchanges also updates day-ahead schedule until Gate Closure. Also, before market day ahead, the System Operator manages network constraints and after that it carries out the balancing market announcing the balancing bids to activate at Gate Closure. System Operator solves imbalances from Gate Closure to Real Time as well considering balancing bids and other pre-contracted ancillary services (i.e. fast reserves). The Transmission System Operator (TSO) is the responsible of assuring system's security and providing an adequate quality of supply by managing the ancillary services which include active and reactive power reserves for balancing power, frequency and voltage control.

Ancillary Services (AS) are distinguished from energy products, are services associated with the production, transmission, and distribution of electric power and are necessary to guarantee the quality, security, and efficiency of supply. They allow system control and dispatch, reactive and voltage support, regulation and frequency response, energy imbalance.

Grid users support the TSO to maintain the balance with contracts that could inquire payments or not from availability and/or activation of power reserves [13]. Closer to real time, operating reserves accorded before can be automatically or manually activated, turning these balancing resources into effective balancing energy. Additionally, emer-

gency services could adjust the dispatch of generation groups or produce interruptions responding to TSO requests.

Differences in electricity markets around the EU are calling for an integrate electricity market which still uses sequential markets, day-ahead, intra-day and balancing but with common rules.

Ancillary services mentioned, in Europe, are being harmonized and classified as follows: [3]

- Frequency control which consists of three elements:
 - Primary reserve (Frequency Containment Reserves, FCR): automatic balance between generation and demand, using rapid response (maximum activation within 30 seconds)
 - Secondary reserve (Automatic frequency restoration reserve, aFRR): centralized and automatic function whose objective is to regulate generation output in a control area to exchange energy with other control areas at the programmed levels, and return the frequency to its set value in case of a (major) deviation, thus restoring primary control reserve. Activation between 30 seconds and 15 minutes.
 - Tertiary reserve (Manually Frequency Restoration Reserve, mFRR): automatic or manual change of the generator operating point (mainly by re-scheduling) to restore an adequate level of secondary control reserves. The maximum activation time are 15 minutes

- Reactive power for voltage regulation is essential to establish and sustain the electric and magnetic fields of alternating-current facilities and has a direct effect on system voltage.
- Power restoration (Replacement Reserves, RR) which is the system's capacity to return to full operation after a massive failure or blackout involving generation resources.

Regarding the wholesale markets, the countries studied deepen in this thesis are managed by different operators: Spain is operated by *Operador del Mercado Ibérico* (OMIE), while France, Great Britain, the Netherlands are managed by *European Power Exchange (EPEX) Spot* and *Nord Pool* operates in Finland.

Currently in Europe, most balancing markets (of power and reserves) for the procurement and settlement and real-time operation are local in scope and mainly managed independently by each TSO. However, in line with the Guideline on Electricity Balancing (GLEB) regulation, some initiatives are done to balance energy among

neighbouring TSOs with a set of network codes [14]. Capacity Allocation and Congestion Management projects affect day-ahead and intraday markets aiming to have reliable pricing of cross-zonal capacity reflecting congestion. The Price Coupling of Regions (PCR) initiative aims to joint clearing day-ahead market in Europe while XBID Initiative is a platform which coordinates intraday markets in Europe [15].

The GLEB regulation became effective in December 2017 with the goal of redesign harmoniously European balancing platforms at different time scales. Definition of balancing products and corresponding platform still under harmonization, three categories of the operation reserves are observed:

Platform	AS product	Time of activation
TERRE	Replacement reserve (RR)	Slowest activation time, up to 30 min
MARI	Manual frequency restoration reserve (mFRR)	Equivalent to tertiary reserve, less than 15 min
PICASSO	Automatic frequency restoration reserve (aFRR)	Equivalent to secondary reserve

Table 1. *European operation reserves under harmonization*

As a result, some or all parties need to adapt to changes caused by the harmonization, such as the price limits imposed on the market, the length of the market session, and settlement rules; particularly, in reference to operation reserves, balancing service providers (BSPs) and balance responsible parties (BRP) as defined in the GLEB.

Balancing service providers (BSPs) can offer balancing services (capacity and/or energy) to the TSOs, who in turn use these services to balance the system. These providers could be generators, demand response facilities and storage operators

Balance responsible parties (BRPs) shall keep their individual sum of the energy volume physically injected or withdrawn from the system in balance or help the system to be balanced, as they are financially responsible for the imbalances of their portfolios. This could be electricity producers, consumers and retailers.

For this reason TSOs are cooperating to define technical rules and products as shown in [3]. At this point, [16] has made a comparative among balancing markets of the three most developed countries in Europe (Austria, Germany and the Netherlands) with wide information as for example an approach for high integration of Distributed Energy Resources (DER) under different conditions which reflect large differences between European Member States such as administrative requirements and DER aggregation, characteristics of auctions, minimum sizes of bidding, pricing rules to remuneration and other aspects related to market access. It is also remarkable that The Dutch

market is the only one in which balancing energy is procured separately from balancing capacity.

Electricity markets organisation and operation described above will help to understand what Demand Response is, how it works, its impacts and some changes needed in electricity markets for its deployment.

The Electricity Directive [17] defines Demand Response as *“the change of electricity load by final customers from their normal or current consumption patterns in response to market signals, including in response to time-variable electricity prices or incentive payments, or in response to the acceptance of the final customer's bid to sell demand reduction or increase at a price in an organised market as defined in point (4) of Article 2 of Commission Implementing Regulation (EU) No 1348/2014, whether alone or through aggregation”* [17]. Conceptually, DR is a flexibility service that is specified by direction, size, time and location [18].

EU DR market is still in the early development phase and fragmented due to national regulations in Member States. DR has a great technical and economic potential while promoting the interaction and responsiveness of the customers.

In economic terms, consumers' usage of electricity is usually fairly inelastic in short time frames since the consumers do not pay for the real price of production; if they did pay a price according to the real price, they would choose to change their use of electricity according to prices. Exceptions from this affirmation usually are large industrial consumers who are elastic when their operations process changes cost are lower than electricity cost.

Electricity produced by generation units are dispatched in order, starting first with generators with the lowest marginal cost (lowest variable cost of production) until satisfy the instantaneous electricity demand. In most power systems, the wholesale price of electricity represents the marginal cost of the highest cost generator that is injecting energy.

Figure below shows DR effect on electricity demand elasticity. The inelastic demand in the electrical power market is represented by curve D1. Supply curve S is based on the marginal cost, cheaper generations produce first. The high price P1 associated with the inelastic demand D1 is extrapolated off the point of intersection of the supply curve S and the demand curve D1. When DR measures are introduced, demand becomes more elastic, represented with curve D2. The new equilibrium point given by the same supply curve S and the more elastic demand curve D2 gives a much lower price.

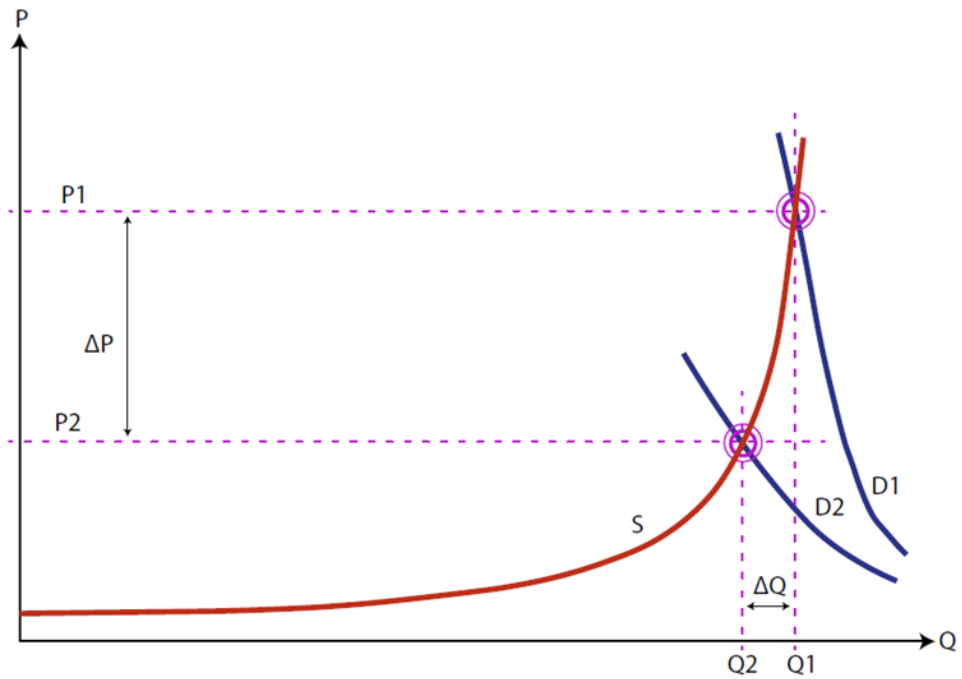


Figure 2. *DR effects on a quantity (Q)-price (P) graph*

From the figure and based on current electricity markets organization a small reduction in demand will result in a big reduction in general cost and, in turn, a reduction in electricity price.

DR also causes some impacts on the electricity markets as expressed along this thesis. On the one side, economic benefits are triggered for both the grid and the customers. Operation benefits on power systems as reliability improvement (can be able to follow production variations) and, in the long term, the lowering peak demand as well. On the other side, DR application has some disadvantages as the amount of adaptation needed, coordination of all stakeholders including the establishment of roles and more barriers that seen in chapter 5

As defined in the Electricity regulation [19] a Balance Responsible Party (BRP) is a market participant or its chosen representative responsible for its imbalances in the electricity market. This actor could use demand response as a tool to better balance their portfolio and optimise sourcing costs. BRPs are the key users of flexibility, because demand response enables accurate adjusting the electricity balance on a shorter timescale [20]. The greatest challenge and the most valuable fact from DR are that it can provide ancillary services but more technical requirements needed as well [21].

As mentioned, power systems are organised in successive electricity markets with different time scales and with their own rules for transactions. These differences mean that for DR participation, different requirements for each of the markets are necessary

according to the rules and the time-ahead to the delivery of the service, which in order are long term contracts (futures), day ahead markets, intraday markets, balancing markets and reserve markets. In figure 3 it can be seen which the DR option intervenes in the electricity market, despite it has been taken from the USA markets has similar application to EU markets. It is remarkable from the figure that ancillary services are contracted in advance, but the dispatching is done on the day-ahead economic dispatching and the operation according to the time of operation of ancillary services. As closer to the delivery, more valuable is the power or services that could be provided, which is also applicable also to DR. More details of DR categorization and operation are explained in next section.

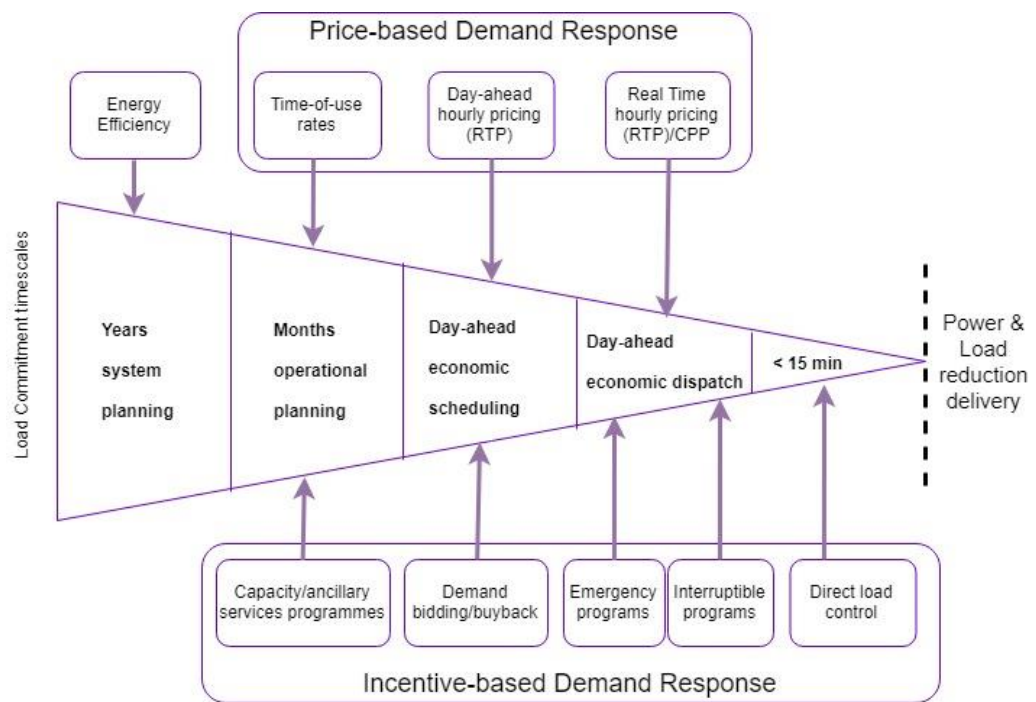


Figure 3. DR operation in electricity markets (Taken from US market [22])

2.2 Control mechanisms

Models and simulations to carry out DR are presented in two manners: using an aggregator to represent the flexible behaviour of a large number of demands in existing market models or as direct load control both uses motivated by the financial benefits that it produces. In both cases there exist different control needs and capabilities for balancing on both the aggregator and the consumer side. In indirect models, large information flow allows more economically efficient outcomes while in direct control mechanisms certainty of response should be higher than computational cost and the loss of economic efficiency to be profitable.

General representation DR bidding through an aggregator can be seen in figure below. Aggregator (which aggregates DR resources) could bid as other power plants in the markets, the difficulties are on the technical requirements that DR must have:

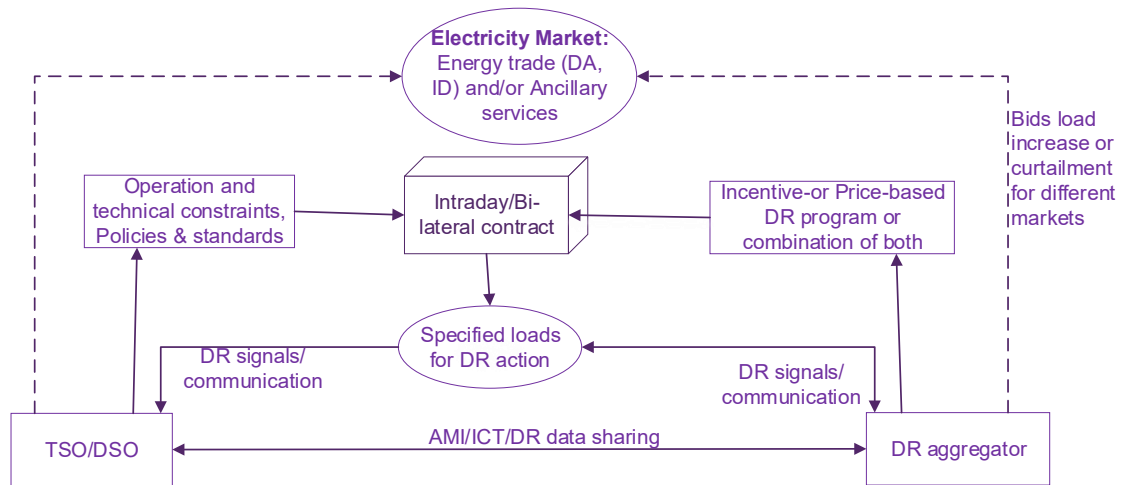


Figure 4. *Energy market Demand-Side Bidding*

2.2.1 Indirect control

Indirect control strategies usually count with a new actor: the aggregator, Virtual Power Plant (VPP) or also called flexibility operator. This actor represents a combined group of DR resources, often with small amount of capacity, which can be operated like a big power plant. Aggregator itself is an important enabler for DR because acts as mediator for consumers, protecting them from onerous technical prequalification measures and from costly duplication of procedures.

The aggregator could encompass the role of a retailer, a flexibility manager, and a balanced responsible party or market agent, needs to solve optimal scheduling and bidding problems to manage their prosumers' resources and participate in the power markets in an efficient way.

Another role for DR aggregator is that can contribute on voltage quality of grid by investing on some compensators, such distribution static VAR compensators (dSTAT-COM) in unbalanced three-phase distribution grids, providing in that way ancillary services [23].

The aggregator has much information about the amount of demand that could control in each moment because of contracts signed with customers in advance and automation systems. The price of the response is difficult to evaluate, expected response can be induced by prices, need for ququality of supply or stresses caused on the grid.

Because of that, depending on the necessity, the information available, and the geographically diversity prices may vary.

Optimisation of aggregation is made by combining two mechanisms: telemetry and financial aggregation [24].

- Telemetry allows the aggregator to combine bids and power flows. The aggregator controls the optimum dispatch of energy with its own algorithms.
- Financial aggregation only allows for the aggregation of bids while the dispatch of energy is handled by the TSO which does not allow the aggregators to use their own dispatching algorithm to take into account consumer behaviour [25].

Figure 5 also represents how the introduction of the aggregator in the energy supply chain is and which are their interactions with other parties. As seen, it has a lot of information and interacts with all stakeholders.

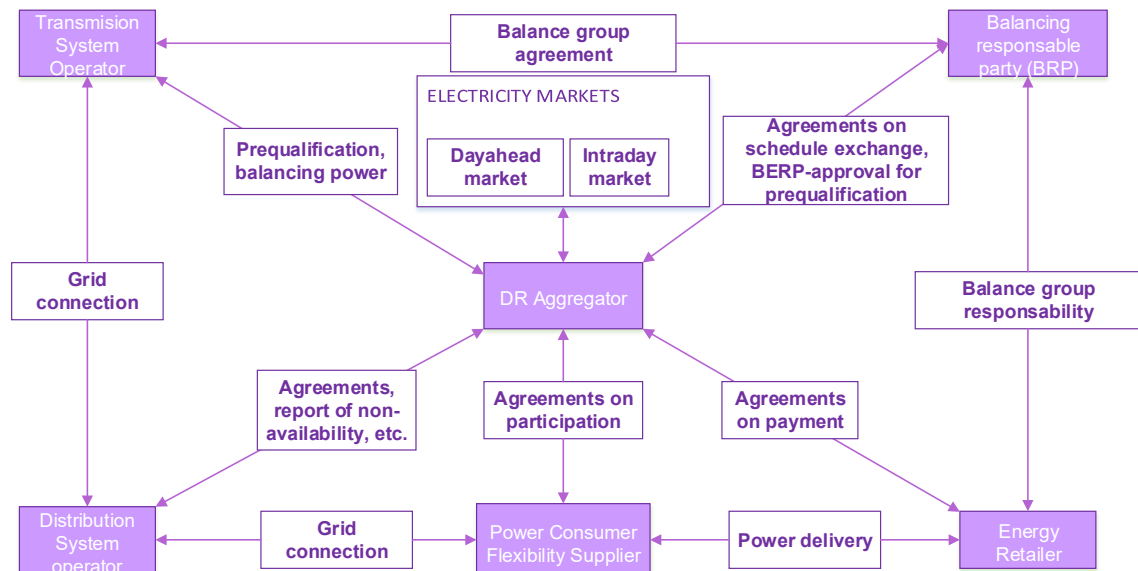


Figure 5. Indirect control organization

Table 2 shows the benefits that this figure can proportionate to the current electricity market stakeholders that as seen in figure 5 has influence on all of them:

Actor	Type of services	Description
DSO	Peak load shaving	Smoothing the aggregated load curve
	DG Supply optimisation	Adapt consumption to DG of a determined area
Retailer /BRP	Portfolio balancing	Adapt actual consumption to day-ahead prediction avoiding extra costs of additional electricity purchase

Prosumer	ToU optimisation	Reduce energy bill by load shifting recommendations
	kW max Control	Reduce prosumer's maximum load consumed within a predefined duration
Power exchange	Self-balancing	Revenues from differences in prices of buying, generating, and selling electricity
	Load optimisation on Day-Ahead Market	Act as generator and/or consumer if reaches the requirements
	Intraday Market	Participate for profit maximisation
System Operator	Balancing Market	With some requirements, can offer balancing bids
	From Gate closure to real time	Participate with pre-contracted ancillary services

Table 2. Services offered by aggregators to different stakeholders

2.2.2 Direct control

Direct control involves direct communication between the “prosumer” and the retailer, DSO or TSO in cases that prosumer is connected to high voltage network. Direct control counts with individual appliances and detailed information on their interactions with the surrounding environment.

This type of control is more computationally and communicational intensive, it drives fully automated solutions. That allows a more precise response and individual control set-points can be sent to each appliance, facilitating control of demand response at the highest possible geographic resolution.

An important application of direct control is in Frequency Containment Reserve (FCR). Primary control requires fast response to frequency measurements and deviations; it works for short period within seconds. Due to the high automation that users of this way of control have there is less error from requested operation which makes it the appropriate mechanism to provide the primary control ancillary service. For this participation to be possible, requirements should be accomplished by the consumer, as the minimum bid size, time of response and other technical requirements.

2.3 Key market drivers for DR

Factors that drive properly the development of DR should be outlined. Five drivers perceived are legislation for retirement of coal thermal power plants, rising electricity prices of retail across the globe, expansion of distributed energy generation, growth in electricity demand owing to Electric Vehicles (EVs), and legislation approved at the EU level. At this point is important to mention technologies which enable DR more efficiently which are deepen analysed in subsection 4.2, these are: advancements in Information and Communication Technology, Internet of Things (IoT) and the Deployment of 5G, growth in Advanced Metering Infrastructure (AMI), Smart devices and analytic software.

2.3.1 Legislation for retirement of coal thermal power plants

Most developed countries are eliminating their base load thermal power plants, some because they are reaching the end of their operational lifespan and others due to environmental reasons. The United States closed in 2018 a little over 13 GW from coal-powered plants [26]. Last lustrum there have also been nuclear plant closures, mostly in Japan and South Korea. The pressure made on the energy supply to the grid gives priority to DR deployment as the alternative to this reduction of power plants. Moreover, in Europe, more than half of all coal plants are now cash flow negative (mostly due to coal cost, emissions rights costs, wind power penetration and marginal cost supply are less used and decreasing subsidies to coal because of awareness of climate change).

Although there is no EU-wide policy that directly addresses coal-generation, since 2008, it has fallen by 20% in volume, and will fall further over time. Several European countries have announced plans, to eliminate the use of coal for power: UK by 2025, Finland by 2030, France by 2022 and the Netherlands by 2030 [27].

2.3.2 Rising electricity prices across the globe

Electricity prices have increased steadily over the last 10 years. In the United States, the average price of electricity has risen by 15%, from \$0.08 in 2006 to \$0.11 in 2016 [28]. In Europe, the average has also risen and differences are significantly different between countries (mainly because taxes and subsidies). Table 3 shows this variation prices, but without including taxes. In most countries taxes and subsidies have increased from 2010.

TIME/GE O	EU	Spain	France	Netherlands	Finland	United King- dom
2008	0,1583	0,1366	0,1213	0,1769	0,1223	0,1458
2009	0,1640	0,1577	0,1206	0,1979	0,1296	0,1466
2010	0,1678	0,1728	0,1283	0,1767	0,1325	0,1386
2011	0,1800	0,1981	0,1383	0,1802	0,1540	0,1433
2012	0,1884	0,2190	0,1392	0,1850	0,1549	0,1682
2013	0,2001	0,2228	0,1524	0,1898	0,1578	0,1741
2014	0,2039	0,2165	0,1585	0,1841	0,1563	0,1918
2015	0,2088	0,2309	0,1676	0,1986	0,1552	0,2125
2016	0,2037	0,2185	0,1685	0,1620	0,1541	0,1951
2017	0,2035	0,2296	0,1704	0,1562	0,1581	0,1766
2018	0,2053	0,2383	0,1754	0,1706	0,1612	0,1839

Table 3. *Electricity prices for household consumers [29]*

Normally, peak demand prices are higher than the average unit price of electricity during non-peak times. Volatility and levels of electricity prices could increase DR curtailing consumers' loads since they can affect the market [30]. That would decrease the purchase of expensive peak power on the day-ahead and intraday markets. With DR end-consumers could have savings in electricity bills in the long term. Other savings will be observed therein.

2.3.3 Expansion of distributed energy generation

DERs often increase the gap between electricity supply and demand due to the variable generation. RES integration reduces system inertia and frequency response, increment frequency variations and also increments imbalances in day-ahead market due to its intermittency caused by climate conditions and the difficulty to predict the production accurately which cause stresses to grids. Despite uncertainties, DERs are able to participate in the wholesale electricity market and have the flexibility to adjust supply in response to an event signal from the energy service provider in order to manage imbalances. However, back-up generators and energy storage (batteries, flywheels, and pumped storage hydropower) can supply energy permitting consumers owning them to respond at times of peak demand events. DR can leverage energy storage technologies to provide ancillary services as well.

Depending on the region and the regulatory framework, there are multiple ways in which DERs can act as a dispatchable DR in the market:

- A resource traded at the electricity market
- A capacity or emergency resource only
- A resource responding to dispatch signals

2.3.4 Growth in electricity demand owing to Electric Vehicles (EVs)

Plug-in EV sales in Europe reached 408 000 units in 2018, 33 % higher than in 2017 [31]. The demand for EVs and their related charging requirements is expected to raise peak power demand globally. This growth, if not strategically planned, would lead issues to the power grid. However, from the wide connections and capacity of the batteries of electric vehicles some benefits as DR resources can be contemplated. The impact on the grid of EV deployment will depend on the grade of application of the following three factors:

- The type of charging technologies used.
- Deployment of alternative energy sources including renewables and storage.
- Pricing mechanisms incentivizing customers to reduce peak loads and to provide DR.

Load shifting from EV is very easy to carry out without the need of last technologies and can provide ancillary services. Moreover, new charging stations infrastructure apart from charging up the EV could also feed energy back into the grid and control the flow responding to local needs. As the EVs in operation increase, aggregators or DR services need to organize their implementations and design price signals and information flows according to their preferences, needs, revenues and/or time-of-use prices offered. These DR measures would be very profitable to consumers since reducing peak loads.

2.3.5 Legislation approved at the EU level

With the Energy Efficiency Directive (EED) [32], European Commission is pushing Member States to open to electricity market conditions for DR. The level of its implementation, development and measures differs across Member States as it is seen throughout this dissertation. A high budget within the Horizon2020 research and innovation programme encourages investigating about DR deployment and grants to promote customer investments. There are many European projects managed by the European Network of Transmission System Operators for Electricity (ENTSO-E), private companies, researchers, innovation centers and universities working towards this development.

More important for DR application across Europe is the “Clean for all Europeans” Package which was proposed in 2016 and has finally published its 8 legislation proposals on June 2019.

3. CLASSIFICATION OF DR

There are different programmes designed to achieve the response in electric usage and in electricity markets. These programs are capable to coordinate the electricity use with power system operation. For that to be possible it is important to know which the different resources for DR exists: distributed generation, dispatchable load, storage and others capable to modify the power supplied by the main grid.

DR programs can be classified according to diverse criteria as shown in literature. DR can have reliability, security or economic aims [33], as mentioned in the introduction. Also, depending on the factor that provokes control the DR units to keep the system within the operating limits [34], can be emergency-based, technical-based or price-based, which is compared with a traffic light concept, red, yellow and green, respectively, according to the state of the power system [35] [36][37]. In reference to the origin of signals that respond exist system, market or local conditions requirements as well. There are load, frequency, voltage, capacity, power quality, price, etc. response programs according to the type of signal provided [33][38][39] [22]. Finally, taking into account the dispatchability of DR in the markets, incentive-based programs or time-based rates are distinguished [40], this last classification is the most common used.

3.1 Types of DR programs

In 2008, DR was already divided in two main categories mentioned: Incentive-based and price-based demand response [41]. Neither form of explained DR is a replacement for the other. It is necessary to enable both to adjust to consumer preferences and maximize the number of benefits for consumers and the system.

Figure 6 shows that classification. First categorization is due to dispatchability of DR: Non-dispatchable programs are Incentive-based programs and dispatchable ones are price-based programs. Further, reliability, security and economic are aspects which induce the decision of dispatchable DR and time-sensitive pricing induces to realize in non-dispatchable DR. Definition of these programs are explained in this subchapter although most of the programs are not applied widely yet in Europe and others are expected to be applied soon in some markets.

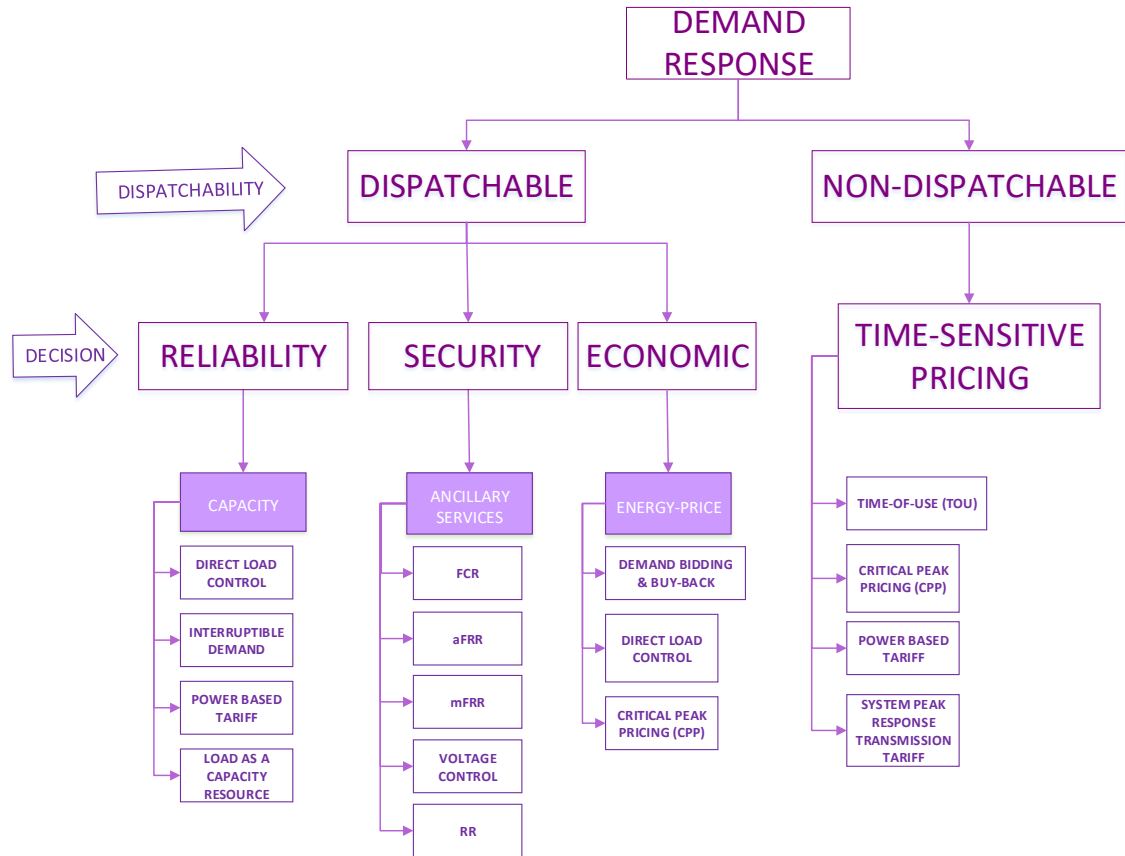


Figure 6. *DR categorization*

Despite of this classification, DR is a complex system rather than a simple price-driven or event-driven mechanism as defended by researchers [42]. For explanations below, participants can be understood as large load or small-scale loads aggregated by the aggregator.

3.1.1 Incentive-Based Programs (IBP)

Incentive-Based Programs are also called explicit or dispatchable DR. It is focused to serve the objectives of supply in the wholesale, balancing and ancillary services markets as large consumers or by aggregation. It is achieved with pre-defined contracts which permit to have a control of the possible effects and does not take into account the parallel savings on the final electricity bill of electricity users [10]. At the same time, IBP can be divided into classical or market-based programs:

- **Classical**

In this case, when customers participate, they receive participation payments, usually as bid credit or discount rate [41]. Load response programs are further divided into direct load control, curtailable load, interruptible load and scheduled load [43].

In **Direct Load Control programs**, utility companies are able to control remotely the equipment; they would shift to the low consumption operation state or even shut down (intentional brownout) participant equipment on a short notice. With brown outs, system operator normally slightly reduces voltage frequency in order reduce the needed electricity transport and generation capacity while still maintaining electricity supply quality within limitations. From DSO point of view this application of DR can be use when the network infrastructure is overloaded or to manage voltage control which is a local problem. Retailers can be motivated to balance their portfolio and maximise their financial benefits. Equipment using these programs is typically air conditioners and water heaters used by voluntary residential customers and small commercial customers.

In **Interruptible/Curtailable Programs** participants are asked to reduce their load to predefined values to thereby reduce peak demand. From other point of view, utility companies do the curtailment of electricity supply. Some applications (in distribution level) use this program to increase the hosting capacity for DR. This type of program is mandatory; participants who do not respond can face penalties, depending on the program terms and conditions.

- **Market based**

Market based programs are characterized by the reward of money for the performance of the customer, the performance are the actions taken when critical conditions occur [41]. Its classification includes Demand Bidding, Emergency DR, Capacity Market and Ancillary services Market.

Demand Bidding programs (also called Buyback) are the ones in which electricity consumers exchange the curtailment of the electricity consumption for revenue in the form of power load curtailment bidding. These programs are market mechanisms that translated to European operation refer to the access to intraday market trading. Customers participate by bidding, a bid to be accepted need to be lower than the market price. When a bid is accepted, the customer must curtail his load by the amount specified in the bid or face penalties. When using these programs, consumption parties are able to negotiate the price according to the amount of load reduction.

On the other hand, **Ancillary services market programs** permit customers and BRP to bid on load curtailment or increase consumption responding to FCR, aFRR, mFRR, voltage control or even RR. Once bids are accepted, participants have revenues for the contributions for the security of the grid.

Finally, **Capacity Market Programs** are supposed to guarantee the supply if additional energy is needed. Currently capacity markets doesn't exist in all European markets and these mechanisms have different designs [44]. Regulation (EU) 2019/943 [19] sets out new rules on existing capacity markets with the aim to minimise or even eliminate them across Member States. Member States will have to justify its use, because of that, this type of DR is not expected to be implemented in the European framework. Negotiated amount of load reduction with the corresponding prices are used as the reserve energy for the electric grid which block competitiveness, principal reason why it desired to be eliminated. In the case of the application of this type of DR, customers have revenues from being able to provide services.

3.1.2 Price-Based Programs (PBP)

These programs, also called Implicit DR programs or non-dispatchable programs, are based on electricity tariffs which vary customers' patterns of energy consumption depending on their criteria to time-varying electricity prices/network tariffs. These tariffs reflect the value and cost of electricity and/or transportation in different time periods. In the past, the objective was to flatten the demand curve by offering a high price during peak periods and lower prices during off-peak periods. Currently, the ultimate objective is to balance supply-demand in every moment based also on a dynamic pricing. These pricing rates which include dynamic pricing are shown in Figure 7:



Figure 7. Time-based pricing options for DR management

- **Time of Use (ToU)**

The basic type of PBP are ToU rates which are the different rates of electricity price in different blocks of time along the day. The simplest ToU rate has two-time blocks; the peak and the off-peak, while in more developed cases the day is divided in 24 hours. The rate design attempts to reflect the average cost of electricity during different periods. Expensive tariffs are during peak periods and cheap rates during off-peak pe-

riods, usually this happens during night hours, called “night-valley filling” behaviour [45] as seen in Figure 9. Some problems from growth of that possibility of the unique existence of two block of time are producing the contrary effect, more demand and more fluctuations during nights.

The aim of ToU rates is to reduce the fluctuations in demand and reduce the generation infrastructures for the same total consumption, optimising the efficient usage of the grid, generation, transmission and distribution resources.

Some advantages of ToU pricing program are that are easy to follow and have a stable daily participating ratio. Same ToU pricing portfolios during the same season help consumers to understand, follow, and plan easier their daily electricity consumption portfolios with very simple automation. At the same time, robust price is a disadvantage. A study [46] shows how from a single household a peak demand occurs right after the price drops from peak hours to off-peak hours, [42] demonstrates this phenomena pricing program, which can be translated to the grid level. It exist a reduction of the overall electricity demand during peak hours but creates a new much bigger demand peak during the off-peak hours, a good example that reflects that is electric heating that uses ToU pricing during a cold day.

- **Critical Peak pricing (CPP)**

This type of program is superimposed on ToU rates or to normal flat rates. CPP is usually combined with other PBP to maximise the benefits. Normally, CPP rates are higher than ToU pricing values. CPP prices are applied during high wholesale electricity prices so the frequency of its use is limited. In most cases, is used only a few numbers of days or hours per year by larger commercial and industrial customers in USA.

In the European markets this type of dynamic pricing could not be possible because changes in tariffs have to be informed to customers some months in advance. What exist in Europe is power based tariffs which medium and some low voltage customers have contracted them. These tariffs are determined in advance and customers carry out their activities according to the contract. The contract prices could have been negotiated and designed to benefit involving parties.

Some advantages of this program are that is easy to follow, is effective on shifting peak energy consumption, and incentives can be visualized. As is it focused on system reliability some disadvantages are also observed; event driven, customers need welfare can be influenced and is not as effective on reducing energy cost as other types.

One application considered by the Californian ISO was to reduce loads during summer, from noon to 6 p.m, when load from air conditioning units were excessive [47]. Also, in California, the delivery of day-ahead values to consumers was designed through social media such as newspaper, text messages, and websites. Results of application of these programs in previous cases are presented in [42].

- **Real Time Pricing (RTP)**

RTP programs reflect the real cost of electricity in the wholesale market, which is only a part of the total cost of electricity for the customer. Thereby wholesale prices vary continuously and customers are informed about them one hour before or on a day-ahead. Many economists are convinced that these programs are the most suitable for competitive electricity markets and should be the central objective of policymakers. Prices knowledge and automation could make demand-supply elasticity more understandable to utility companies [42]. Smart meters infrastructures are needed for its application on residential customers.

In Europe, for this type of program it would need to be added the grid services prices and taxes to the cost for the residential customer. For example, in Finland, energy part is only about one third of the total cost for residential customer. The other two third correspond approximately in the same amount to grid services and taxes. Each Member State has their tariffs.

3.2 Customer response categorization

When referring to DR in past years, they consisted on interruptible or curtailable services from large customers. Nowadays, smart meters, home automation, control technologies and advanced communication enables complex application of DR, with domestic customers, EVs and data centers participation. Classification of customers can be visualized in figure 8 and explained further in this chapter:

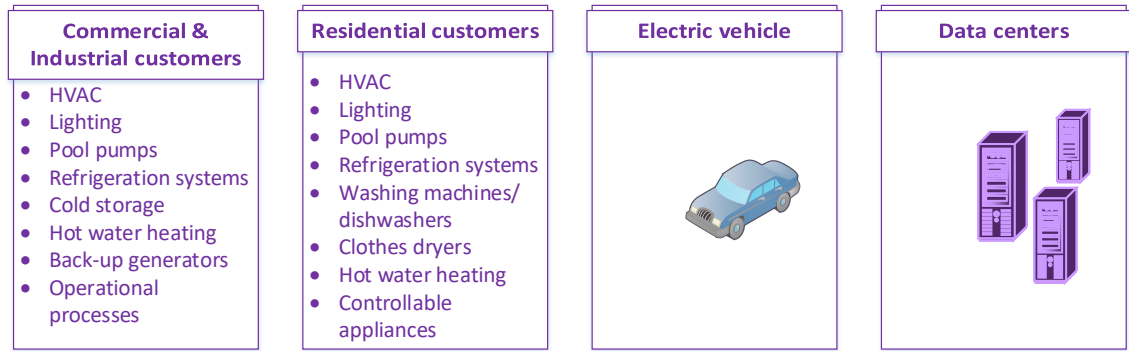


Figure 8. *Potential customers for DR*

Customers are referred participate voluntary or mandatorily in DR programs with their loads consumption. DR can be carried out directly with the utility, or through an intermediary. In the organized markets, such as wholesale electricity market, aggregation of small scale end-customers is presented by the intermediaries known as aggregators. Industrial customers can participate directly to the wholesale electricity market and they also actively operate their DR resources for internal use and have revenues from different markets. Often it is necessary, for customers, technical and financial support from the utility to be able to react to their signals automatically [48].

Figure 9 shows customer effects on the demand curve when they provide DR. DR can be achieved by three general actions [49]:

- **Reducing** their energy consumption through load curtailment strategies, reducing their electric usage during critical peak periods when prices are high without changing their consumption pattern during other periods. This is called “peak clipping”. For instance, it is achievable changing temporary thermostat settings of air conditioners.
- **Moving** energy consumption to a different time period according to high electricity prices of peak-demand periods, load shifting. Costs in this type are different between residential or industrial customers due to rescheduling of the activities. From this move arises the concept of “valley filling” which aim is to consume more when demand is very low and production is higher, especially when is provided renewable energy resources.
- Using **on site generated energy**, which importance is growing because of the deployment of DG, thus limiting their dependence on the main grid. This could help to peak clipping or load shifting more easily. In a near future, if on site generated energy could feed a battery, load shifting could be done without compromising customer activities.

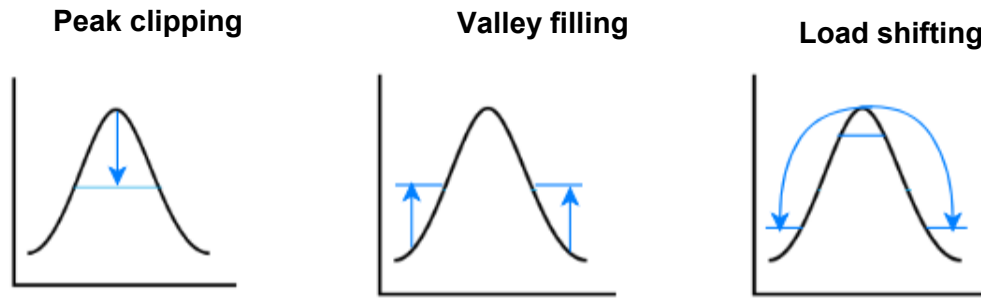


Figure 9. *DR adjustment of load shapes*

3.2.1 Commercial and industrial (C&I) customers

DR programs are very interesting for industrial electricity consumers in the smart grid environment. The C&I sector currently represents a bit more than the half of the world's total energy consumption [50] and more than a third of total electricity consumption in Europe. The simplest form of participation is to postpone some production operations to an overnight shift and benefit from lower-cost off-peak energy. Industrial DR is already commercially provided in France, Ireland, UK, Belgium, Switzerland and Finland [51].

Large C&I customers usually have the most advanced technologies for controlling the loads within their facilities and may more easily participate in either wholesale or retail electricity markets. Moreover, this proves that DR environment is much more attractive for large consumers with higher electricity consumption [52].

Flexibility achievable from industrial customers requires detailed modelling to estimate it. Mainly industrial customers operations are already design with efficiency in mind and their constraints only allow small changes on power consumption [7].

For the optimization of power load scheduling among industrial costumers there are many problems going on. There exist many studies trying to optimize the smoothing of the load curve, improving the reliability of the power grid and reducing the costs for electricity consumers [53].

Mckane et al. [54] differentiate two main problems for modelling Industrial demand response: interdependencies between machines in production lines are complex so are mathematical model and each industrial process is different, and consequently is not possible to design an universal model for DR program. Cui and Zhou [53] summarizes the models and solving methods from previous studies focused on the power load scheduling problems in the industrial plants.

Temporary inventory control done by the shutdown of machines could adjust temporary buffers in manufacturing facilities. These models of control are categorized into single-objective models and multi-objective models according to the objective function for industrial power load.

Single-objective units can be divided into schedulable or non-schedulable. In both, the objective function, as intention for industrial plants, is to minimize the overall energy cost and maximize the revenues from energy while accomplishing the business plan objectives of the industry that means the amount of outputs established. The model constraints are referred to industrial production process, energy storage, energy generation and electricity purchasing or selling.

On the other hand, multiple-objective models are more complex, they analyse problems with more variables. They can be classified between optimally theory-based scheduling models if depends on a single person decision or game theory-based scheduling models if regarded as multiple decision-making process.

Some important load to consider within industrial customers apart from process loads are HVAC systems, which are not directly involved in the production process but represent a great amount of industrial consumption.

3.2.2 Residential customers

Residential sector can be aggregated as Block of Buildings (BoB) [12]. These customers are characterized by relatively small and limited types of load curtailment strategies like dimming lighting levels, decrease the temperature set points of air conditioners, etc. Soares et al. [55] describes potentially controllable demand in the residential sector although residential power management, decisions and best response actions based on price signals. Logically, as [42] mentions that household responsiveness is proportional related to its income and energy consumption, when household's income increases response decreases, this could be related to the lack of awareness of DR benefits for this customers. Benefits for residential customers are not only economic, they can improve quality of electricity supply which without it, installations and devices connected to grid could be damaged.

The lack of controllable devices makes DR programs far to be mature; it will be deepened analysed further down. Moreover, residential customers are not motivated to invest much in order to manage their electrical usage, but the deployment of new standards and technologies such as AMI are lowering market prices of technology and making it more competitive, so DR is more accessible.

Many investigations and simulations of the viability and potential of residential DR are carried out. For example, only considering HVAC in residential customers, *Avci et al* case of study [56], efficient HVAC load control strategy for residential units responding to real-time pricing data from the utility company is compared with numerical experimentation. The investigation also takes into account the thermal comfort of the consumer by using a thermal discomfort tolerance index. Other researches propose a two-degree-of-freedom system to operate HVAC in residential customers, this is the case from Anna and Bass [57] which simulates the decoupling of the heat pump output from the indoor temperature and using a bigger thermal storage unit [57]. Results of simulations expect to improve the control strategies according to real-time pricing, weather forecasts and aggregate DR of a house set.

In European framework, residential DR is not very common. Member States need to incentivise residential customers DR. This could be caused by the lack of awareness of residential potential, population think that their collaboration is negligible, but as DG increases, intermittency increases and DR is more and more necessary. Renewable sources supply are jeopardizing reliability of the system and energy cost. Smart meters roll-out is a

potential instigator to capture the value of residential DR.

3.2.3 Plug-in electric vehicles (PEV)

Over the years PEV have increase their importance as a type of DR customers. Due to the increasing penetration of PEVs into the market, it is expected to represent an important load on existing distribution systems operation in the near future [58]. Likewise, numerous works report how distribution can be significantly impacted by large penetration of PEVs [59], [60].

PEV charging operation can be controlled by the EV customer or in a centralized smart charging way. Smart charging means that BRP, aggregator or retailer or consumer decides which cars to charge, how fast and when. Customer also can control the smart charging by himself based on the total situation at home.

The case studied in [58] simulates both ways to determine the smartest operational decisions to take for the integration to the distribution system operator designing mathematical models. These mathematical models consider minimize losses and balance active and reactive power in the power system. The conclusion that Hafez arrives is that PEV customer behaviour can cause bus voltages deterioration. Notwithstanding, reinforcement of distribution systems and coordinating charging strategies would be

enough to avoid unacceptable variations in voltage profiles and consumer equipment damage [17].

In 2016, CGI made a research study about end-user interaction and smart charging. From analysing three types of user models, they conclude that with financial incentives DR from EV could work, but considering the comfort and flexibility of consumers [61].

3.2.4 Data centers

Before 2010 most of the literature did not contemplate data centers as a type of customers for DR or it was considered in the industrial customers group, but due to its capacity and flexibility compared to conventional industrial facilities, lately, it is seen as a good DR resource. Data centers are one of the fastest growing industries between emerging economies countries in terms of IT service and usage of data.

The term load balancing in cloud computing refers to the homogenous distribution workload between cloud servers. Its aim is to optimize resources utilization, maintain the cost of the data center, reduce the response time and do not reach overloads. For this reason there are many algorithms developed along years about the appropriate distribution [62]. Moreover, the increase development of cloud computing requires more electricity usage.

Besides, to guarantee quality of service, data centers overprovision their servers to address peak workloads. That leads to a huge consumption of energy and unnecessary energy cost and consequently CO₂ emissions. Almost 4% of global operational electricity consumption is from the Information and Communication Technology (ICT) sector [63]. Exact information from data centers is not available but they are expected to consume one fifth of Earth's power by 2025 [64]. According to Google, their global data center operation electrical power ranges between 500 and 681 MW, from which a high percentage of that could be controlled for DR. Data centers challenges are to improve their energy efficiency in server operations and to use renewable energy and energy storage for power procurement [65].

Data centers are often delay-tolerant, hence may be rescheduled to off-peak hours considering deadlines constraints as well. Some algorithms and numerical simulations with real data to participate in electricity markets are done but there is much improvement to make between server operations and power procurement to have a robust implementation of the technique [65]. It is also mentionable the impact that data centers energy management would have to the power grid. Few documents like [66] have the aim to study the minimization cost of energy from the point of view of the power grid.

S. Kwon et al. [65] develop a decision-making model considering mainly delay-tolerant workloads from data centers, renewable energy, energy storage, and the electricity market and via numerical experiments quantifies the benefits of the model. Results show that data centers cut costs and increases the use of renewable energy. Recently [67] proposed an iterative bargaining approach assuming linear for pricing data center DR while also using renewable generation, the algorithm corroborate its effectiveness compared to other algorithms which are social welfare maximization and Stackelberg game.

Other papers focus the simulations on DR programs types. On the one hand, [68] takes into account RTP in deregulated electricity markets and model the data centers' coupled decisions of utility company choices and workload scheduling as a many-to-one matching game with externalities. Model results are compared with the scenario without DR from data centers. Benefits from this application are observed; a reduction of the average contract payment of data centers by 18.7% and an increase of utility companies' revenue which offer an 80% lower electricity tariffs when attracting more data centers as customers, however, there could exist some exceptions due to externalities.

On the other hand, [69] considers data centers and air-conditioning loads for Emergency DR instead of using backup generators. The simulation is based on the existence of a load aggregator who signs contracts with office buildings and transform signals from power grid to instructions to office buildings which should upload the real-time temperature and the amount of data network and both hardware parameters.

Other works analyse workload data centers schedule their loads jointly with local power generation for CPP [70]. The algorithms are designed for the time when critical peak is warned or located at the worst moment and adversary workload shifting. After evaluating the algorithms with real data, the paper concludes that both can respond to utility signals and the combination of the two resources can provide 35%-40% reductions of energy costs, and around 15% of emission reduction.

4. HISTORICAL TREND OF DR

This chapter will focus on past, present and expected DR market trends. It is presented how some limitations have been faced last years and the rapid evolution of market conditions for DR deployment referring to legislative and technical point of view.

4.1 DR review and state of the art

Studies on DR started on early 1980s with DSM programs. In 1988, a ToU rate design process was already described [41]. In 2001, introduction of DERs in deregulated power systems promoted decentralized generation reducing large-scale power plants generation which usually produced GHG emissions [71]. Later in 2003, a pilot covering 43 voluntary RTP programs, concluded that the main motivation behind RTP programs is customer's opportunities for bill savings[30].

In 2008 the ultimate objective of DR was to reduce peak demand, and because of that, a simulation of the effects of elasticity in electricity prices was performed in to demonstrates the effect of DR programs in cases of system contingency [41].

In USA, due to structural rigidity of DR programs, the flexibility in electricity market operations was inadequate and inefficient. For this reason, in 2015, a new operation way for retail customers to interact with wholesale power market was defined conducting USA's electricity markets the most developed for DR application. That integration market operations and simulations are reported in [72]. The study is based on comparing passive responsive customers and proactive demand. Passive customers respond to time varying prices and load reduction instructions sent while proactive demand participation counts on an intelligent energy scheduling agent which collects forecasts like temperature, humidity, customer usage preference, electricity prices and historical data to create a price sensitive demand bid curve. The creation of this curve facilitates coordination and integrates proactive demand participation in wholesale and retail market operations. Problems from its implementation could arise, such as the lack of benefits between intermediate parties, which have they own interests and privacy of participants could be jeopardised as well.

With DR, low carbon and efficient electricity system is easier achievable, for this reason it has been growing worldwide and is expected to continue. Despite the efforts,

many challenges for DR still remain. Simulation and forecasting models of demand require establishing a realistic view of this resource for planning and evaluation purposes.

In future electricity systems the generation-follows-demand perspective is increasingly replaced by a demand-follows-generation perspective. This transition requires dynamic pricing reflecting real-time cost of electricity for consumers. Global DR market is expected to grow at a compound annual growth rate (CAGR) of almost 16% from 2017-2021 [73]. In 2016, a deep analysis of the European state of DR was made [74] and is expected to be actualised every two years.

4.2 Enabling technologies for DR

Intermittency of wind, solar power generation and other market issues are opening opportunities for a range of companies offering services, hardware and software enabling DR and automated control systems. Their relevance varies and some are available worldwide and others uniquely in countries where have been developed [75]. Some of this technologies are smart meters and smart plugs for load control, home energy management tools, energy information tools in order to monitor customer's performance and communication infrastructure for fast response [76].

From one side the enablers are the communication improvements, data management and analysis and from the other side the improvement of technology that gather the data.

4.2.1 Advancements in Communication Technology, Internet of Things (IoT), and the Deployment of 5G

An efficient, real-time Smart Grid communications infrastructure and electricity consumer is the major enabler to further the adoption of DR applications. Digitally connected and distributed intelligent assets will enable the two-way flow of information and energy (this last, used when self-consumption allows injection of electricity, which is a further step for DR) , allowing utilities to efficiently manage increasing complexity [77].

DR solutions have enabled retailers, DSO and BRP to monitor, predict and manage peak-time energy demand of machines remotely. With real-time information, TSO and DSO are able to analyse, predict and act in periods of energy scarcity, and carry out DR.

DR solutions have been already successfully implemented without 5G Unlike before communication technologies; 5G is specifically designed for M2M (machine to ma-

chine) communication. 5G proposes a high bandwidth with the aim to support large volumes of data being generated from the growing number of end-point devices. Multiple telecom service vendors have tested 5G speed ability to provide adequate data transmission capabilities for advanced edge-intelligence applications for DR.

Moreover, one relevant technology among others for DR is Internet of Things (IoT). IoT is improving the current energy systems data management into intelligent cyber-enabled systems. It permits faster and better smart grids development by expanding intelligence to customers and appliances. In spite of that, there is currently a barrier at the smart meter interface. Devices use their own language and IoT technologies should match with it. Differences in language used, devices decision making and competitiveness between developers of this technologies and devices could enable easy expansion of intelligence to smart devices. In the IoT environment, for instance, a washing machine could be controlled wirelessly for demand response purposes [78].

4.2.2 Growth in Advanced Metering Infrastructure (AMI), Smart devices and analytic software

Smart meters, smart thermostats, and automatic control switch, improve the ability to keep track of the real-time electricity utilization in electricity networks and control it.

Smart meters and AMI infrastructure are critical for implementing DR. Smart meters are new generation electronic meters with a capability of bi-directional communication between the end-user and the other parts involved. This equipment is essential whether the consumer is participating in a dynamic price system to which reacts voluntarily or if he has an agreement with a third agent by which allow direct control of his consumption. In the latter case, a higher level of technologic development is necessary with certain possibilities for remote control and intelligent management of the loads, apart from the exchange of information.

The implementation of remotely controllable Heating Ventilation Air Conditioning (HVAC) equipment such as thermostats, water heaters, and alternating current (AC) switches are growing in popularity across North America and Europe as well.

Moreover, advances in ICT and AMI have allowed the development of Home Energy Management Systems (HEMS) and Building Energy Management Systems (BEMS), which allow effective control of consumer loads and more effective communication abilities [23]. These new devices are important for application of DR programmes because they gather data from different devices of households.

Smart meters can be directly connected to WAN or more typically used: AMI network. And AMI network can be constituted by a series of networks called Neighborhood Area Network (NAN). In that last case, AMI networks connect a central unit or data aggregator with the smart meters of a same point of consumption called Home Area Network (HAN). NAN sends information upstream to a Wide Area Network (WAN) until the end of the AMI. HAN networks may communicate with the smart meter so that:

- Price signals and other data can be sent and displayed on-site through the display devices, in-home displays or mobile applications.
- The smart meter provides real-time consumption data to HEMS, which collects the information from flexibility available from consumer.

These networks are the infrastructure that allows automatic response optimizing algorithms of DR, at local or area level. Likewise, consumption control in the reaction to signals can be controlled manually, but it is more efficient and has a greater potential for savings and impact on the system if response is automated. If applicable in households' energy management systems, HAN network is integrated in an intelligent system called Home Energy Management System (HEMS) [79].

NANs and the HANs are susceptible to be built with wireless technologies given their ease of installation and low cost compared to wired solutions. Some used network technologies for NAN networks are WiFi, ZigBee and Bluetooth which adopt standard protocols developed by the IEEE for AMI [23]. WAN networks use all technologies, wireless or wired, either through the telephone cable or by the power lines themselves through Power Line Carrier (PLC), fiber, public wireless, cellular networks as 2G, 3G....

Many companies related to energy management and efficiency are making progress in the development of algorithms that allow the identification of individual consumptions with high precision to make it easier for consumers to make decisions about its use. Some examples of them are Belkin, GE, IBM, Intel, Landys Gyr, Siemens... [80].

Ittron, for example, provides smart meters that comes equipped with an in-built communication protocol (ZigBee®), providing a communication gateway with home electrical devices. These devices are capable of offering real-time data to consumers about ongoing energy usage and also have the ability to control loads available at home [81].

4.3 Legislative framework

Since some years ago, the European Commission (EC) is pushing for the creation of a single energy market to enable more security of supply, climate friendly, increase electricity market competition and to be more responsive [12]. Despite DR services, Europe is still in the early stages of development, with a variable rate of adoption across the different member states. In this subchapter it is shown the interest for European regulatory authorities and institutions to look for mechanisms to implement DR.

Already, in 2005 European Union Energy Policy was created to make mandatory the compromises about Energy concerns.

Since the Lisbon Treaty of 2007, energy policy and the environment are shared competences between the EU and the Member States [82]. This means that any regulatory proposal at European level must take into account the sovereignty of the states to decide their national energy policies. This treaty was signed by all member states and specifies the EU's energy objectives:

- Guarantee the functioning of the European energy market.
- Guarantee the EU's energy security.
- The promotion of energy efficiency, renewable energies and the decarbonisation of European industry.
- Ensure the interconnectivity of European energy networks.

In March 2007, also were stated “20-20-20 by 2020” targets, which the 20% share of renewable energies in final energy consumption by 2020 is the one which affects the most to DR deployment.

Furthermore, exist European Policies advocating for the DR to participate alongside supply in wholesale markets for aggregation. The first was the Directive 2009/72/EC regarding common rules for electricity market, considering generation, transmission, distribution and supply of electricity. Some other objectives stated on the deployment of a 80 % smart metering systems in EU for 2020 and 100% for 2022 [12]. Also, in 2009, during the Paris COP21 climate conference, more than 150 countries set up energy action plans which the World Resource Institute (WRI) foresee to duplicate the renewables energy market for 2030. These initiatives facilitate DG penetration, and as a result, EU has 3 times more renewable power per capita than anywhere in the rest of the world.

The Energy Efficiency Directive (EED) 2012/27/EC¹ constitutes an important step towards DR deployment. The Directive specifies that regulators should encourage DR to participate in the market and network operators are not allowed to discriminate DR providers in the context of contracting ancillary services. On Art.15 (referred to Explicit DR) it encourages to energy efficiency and explicitly urges EU national regulatory authorities to encourage demand-side resources, including DR: “to participate alongside supply in wholesale and retail markets, and also to provide balancing and ancillary services to network operators in a non-discriminatory manner, on the basis of their technical capabilities” [32]. This Directive also requires further actions and the need of technical modalities to participate in the different markets by national regulatory authorities, policy-makers and energy companies. Within this framework, already in 2014, ENTSO-E identified five issues to be addressed to achieve the objectives of the Directive [83]. Part of the application of this Directive is controlled by the National Energy Efficiency Action Plans (NEEAP) that each country reports periodically.

In 2012, Agency for the Cooperation of Energy Regulators (ACER) accepted the Guideline on Electricity Balancing (GLEB) framework. This arrangement strives for integration, coordination and harmonization of the balancing regimes in order to facilitate electricity trade within the EU in compliance with the Electricity Regulation and Directive 2009/72/EC. Specifically, address the roles and responsibilities of stakeholders involved in electricity balancing, the procurement of frequency restoration reserves and replacement reserves, and its activation.

In line with these Framework Guidelines, ENTSO-E is drafting the Network Code on Electricity Balancing. Between 2009 and March 2017, ENTSO-E has developed, jointly with ACER and some stakeholders, eight European Network Codes. This network codes can be classified into three families [84]:

- Market codes aiming more competition and resource optimisation. Setting rules for capacity calculation and allocation, day-ahead and intraday markets, forward markets and balancing markets. [85], [86], [87],
- Operational Codes which goal is to reinforce the reliability of the system through harmonised rules for operating the grid covering system operation, regional cooperation and emergency situations [88], [89] .
- Connection codes establish wide conditions for linking all actors safely to the grid, including renewables and smart consumption [90], [91], [92].

¹ Directive 2012/27/EU, on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC, 25 October 2012

In this Network Codes, there is a high-level structure enabling the participation of demand-side resources across markets and Member States. The Network Code which is crucial for Explicit DR is the Demand Connection one. Demand Connection Code [92], which entered in force in 2016, focus on grid connection requirements for demand facilities and distribution systems. It establishes a common framework for connection agreements between the demand facility owner and/or the Distribution System Operator (DSO) considering TSOs. Also, it addresses the technical requirements and procedures needed to provide DR services in terms of active power control, reactive power control, transmission constraint management, system frequency control and very fast active control for supporting TSOs [92].

A new proposal from early 2017 for a “Directive on common rules for the internal market in electricity” reinforces Electricity Directive’s objectives. It takes for granted DR alongside storage and generation. Moreover, the proposal requires RES and DR penetration in balancing and wholesale markets [93], aspects which are covered by the recent Electricity Directive from June 2019.

Furthermore, the EC launched the Clean Energy for All Europeans Package (Winter Package) in November 2016 [94]. The package includes 8 different legislative proposals covering: Energy performance in buildings, Renewable Energy Directive, Energy Efficiency Directive, Electricity Regulation, Electricity Directive, Risk Preparedness Regulation and Rules for the ACER regulator. Table 4 shows how has been this procedure during las three years:

	European Commission Proposal	EU Inter-institutional Negotiations	European Parliament Adoption	Council Adoption	Official Journal Publication
Energy Performance in Buildings	30/11/2016	Political Agreement	17/04/2018	14/05/2018	19/06/2018 - Directive (EU) 2018/844
Renewable Energy	30/11/2016	Political Agreement	13/11/2018	04/12/2018	21/12/2018 - Directive (EU) 2018/2001
Energy Efficiency	30/11/2016	Political Agreement	13/11/2018	04/12/2018	21/12/2018 - Directive (EU) 2018/2002
Governance of the Energy Union	30/11/2016	Political Agreement	13/11/2018	04/12/2018	21/12/2018 - Regulation (EU) 2018/1999
Electricity Regulation	30/11/2016	Political Agreement	26/03/2019	22/05/2019	14/06/2019- Regulation (EU) 2019/943
Electricity Directive	30/11/2016	Political Agreement	26/03/2019	22/05/2019	14/06/2019- Regulation (EU) 2019/944

Risk Preparedness	30/11/2016	Political Agreement	26/03/2019	22/05/2019	14/06/2019-Regulation (EU) 2019/941
ACER	30/11/2016	Political Agreement	26/03/2019	22/05/2019	14/06/2019-Regulation (EU) 2019/942

Table 4. *Legislative process of Clean Energy for all Europeans package* [95]

The Electricity Directive proposal, the most related to the topic of this master thesis, includes the obligation for all Member States to introduce a legal framework for DR aggregators, enable their access to the market and define roles and responsibilities. In its article 17, says that aggregators should not be required to pay compensation to suppliers or generators but may exceptionally be required to pay compensation to balance responsible parties., the Official Journal publication is very recent, which in turn its application in Member States will result many changes in the European electricity networks.

Although the guidelines of the EC are clear, the Member States are implementing them at a different pace. From technical to legislative point of views disaggregated and heterogeneous contexts and markets still exist as analysed therein. Currently, only France, from all the European Member States, have commercially active agreements in place for independent aggregation, including standardized roles and responsibilities for market participants with respect to DR services and solutions [28]. The number of use cases for DR across Europe are expected to continue increasing until 2024, laying the groundwork for more robust growth for the DR market beyond 2020 [28]. Other examples of these differences are justified with the depth analysis of the five Member States of this thesis.

Other area where policymakers need to cover is related to cyber security in Smart Grids. Minimal measures for cyber security and resilience to operators, market participants and consumers are needed to be integrated in the regulatory frameworks of Member States. The Directive on security of Network and Information Systems (NIS) was the first piece of European-wide legislation on cyber security. With its adoption and the General Data Protection Regulation (GDPR) in 2016, the EC implements the baseline for cyber security following the recommendations [96] made by Energy Expert Cyber Security Platform (EECSP) referring to the energy sector.

5. BENEFITS, BARRIERS AND CHALLENGES OF DR FROM THE VIEWPOINT OF DIFFERENT STAKEHOLDERS

The costs and benefits from DR are difficult to quantify at a macro level [52]. Advantages and inconvenients from DR must be analysed from stakeholders and before that, determine stakeholders' roles and their responsibilities should be narrowed enough and well regulated. Analysing stakeholders is crucial to understand relevant actor's needs, desires and potential barriers to a specific implementation, development or change [97].

Primary stakeholders are the actors which actions lead to DR success.

- **Customer**

Customers are expected to respond to price signals channelled through the retailer, aggregator or a third party which modulates customers' consumption profile. Their interest on DR states on reducing the energy costs, capitalize flexibility in electricity markets and exercise more power on the electricity market. The lack of quantitative understanding of consumers' behaviour and end-use activity adaptive capacities is a significant barrier to design and deploy effective DR programs.

- **Aggregator**

The aggregator promotes and manages the actions economically made under the DR framework. It is a service provider who manages a set of demand facilities in order to sell pools of electric loads of different characteristics as one bigger unit in the electricity market. Without been a retailer of electricity they play the role of intermediaries between consumers and all markets, providing them with manageable loads in certain nodes. Aggregator aim is to help small consumers to participate in the electricity market due to its complexity. Independent aggregators negotiate with their clients the amount of loads to increase flexibility and reliability and reduce participants' risks, is not affiliated to the customer's supplier.

- **Balance Responsible Party (BRP)**

BRP is a market participant or its chosen representative responsible for its imbalances. Each BRP must strive to be balanced in real time, and is financially responsible for the imbalances. BRP's sum of their injections, withdrawals and trades should be balanced over a given timeframe (the imbalance settlement period). Imbalance settlement is a core element of the balancing markets and means a financial settlement mechanism aiming at charging or paying balance responsible parties (BRPs) for their imbalances.

- **Retailer**

With DR, retailers could act also as aggregators; directly or in cooperation with independent aggregators, but some business model factors can make retailers difficult to provide aggregation. The main business of retailers is risk management. Retailing services with DR entail a high knowledge of loads performance but at the same time enlarge their business models by creating a new risk from unknown customer demand which comes from DR of DG, independent aggregators,... Some barriers which slow down their desire of DR deployment are the upfront costs and the uncertainty of revenues. Some retailers rolling out DR programs are *EDF, E.ON, Dong Energy and Helsinki Energy*.

- **Distribution System Operator (DSO)**

DSO is responsible for the final stage of the electric power delivery to the customer premises. Is not expand yet, but if DSO participates in DR business it does as a flexibility buyer. DSO may provide communication services through AMI system to aggregator but in that case DSO does not make decisions. When DR tools are focused mainly for small consumers, managers of distribution networks have the ability to control potential load reductions in each node of the transport network.

- **Transmission System Operator (TSO)**

Their actions are expected to continue to be focused on the management improvement of the system acquired through distributors. In the short term, DR allows to fulfil the standard of service quality at lower cost and in the long term reduce the cost of investment in network reinforcements as seen explained in this chapter.

- **Generator**

Generators are the producers. This actor provides the energy and ancillary services (reserves). When applying DR, this stakeholder is interested on reduce expensive energy generation and the need of capacity reserves in order to participate in intraday and/or balancing power markets according to prices.

- **Policy makers**

Policy makers in EU are principally the European Commission and the national government of the countries. Their interest is to ensure the security of supply, increase the integration of RES, reduce carbon emissions and ensure the economic development. Regarding to DR, their aim should work towards removing administrative barriers to aggregation, clearly differentiate the services and incentivize actors to reveal the true cost in order to have clear price signals.

- **Building Management System (BMS) & equipment manufacturer**

This group is in charge of enabling DR from the technical point. The solutions cover the ICT and automation sector with the aim to ensure the good operation between the technology of the components, the communication and the control in the sectors where DR is applied. Some manufacturers can think that standardization is the best option and others that create devices with their particular language for communication, creating in that way their own business model increases competitiveness.

Secondary stakeholders are those without high power/interest but still playing an important role:

- **Energy Services Companies (ESCO)**

An ESCO is a company that offers energy services which may include implementing energy-efficiency or renewable energy projects. They provide a broad range of energy solutions including designs and implementation of project which permit to achieve energy and environmental goals. Differences from the traditional energy consultants or equipment suppliers from the fact that they can also finance or arrange financing for the operation and their remuneration is directly tied to the energy savings achieved [98].

- **Builder/developer**

Developers and builders construct the infrastructure and have an important role as they define or recommend the project objectives, investment and targets. They can influence the key features and components or in some cases simply executing the work following the specifications from the owner/designer.

- **Maintenance companies**

These companies involve the upkeep of buildings including their energy infrastructures and the surrounding area. They are essential to the efficient and effective running of buildings and their energy systems. As such they are essential to enabling DR by ensuring that the systems and controls are operating as intended. Some ESCOs also offer building maintenance as part of integrated energy supply contracts.

5.1 Benefits

It is believed that system operators transmission and distribution, and end-use consumers can benefit from DR [42]. To quantify DR benefits they first must be explained and later evaluate the consequences on the complex behaviour of power systems.

Neither of these analyses is trivial and is more complicated at macro level. Several studies have analysed changing effects both qualitatively and quantitatively, providing valuable insights and constituting a useful starting point for future studies and dissertations.

In 2008 benefits from DR were already contemplated according to stakeholders point of view [41]. In 2014, more benefits were found as [7] mentions. Follow are resumed the benefits found in literature divided according to main DR impacts but also from the stakeholders and market actor point of view to understand why DR should be engaged [99].

Operating benefits

Grid operation benefits below are mainly from TSO's point of view. Effects of these applications can suppose problems on other stakeholders as reflected on table 5.

Integration of RES to market can help to handle the intermittent generation but also causes the necessity of balancing the network from both the supply and the demand side [52]. DR development facilitates higher penetrations of renewable resources on the power system and improves the ability to **balance fluctuations** from wind and photovoltaic (PV) generation. These balancing applications benefit producers, BRP and TSO.

Security services can be provided by DR reserves, balancing power and load and production changes. Capacity increases which in turn reduce risk of outages events, as well. Moreover, by participating, customers reduce their own risk (to themselves and to other customers) to forced outages and electricity interruption.

DR also permits more diversified resources for the operator. Aggregation of different types of loads carries out **faster ramping** than large thermal generating plants. Many load types can instantaneously adjust power consumption. This available fast reaction time is a key element in ancillary services, particularly for FCR, which is the one the most valuable.

In addition, the **dependence on inter-regional connections** can be reduced and be used when is profitable rather than out of necessity to balance the system. In this point it is also mentionable the handicap that the weather between neighbouring regions is similar (between to cities nearby normally is cloudy or windy at the same time) so the needs may coincide and necessary services may often not be provided from one region to the other.

Economic benefits

Due to more available infrastructure (geographical and temporal) the wholesale price of electricity is lower. DR reduces the general **cost of energy** supply while preserving adequate reserve margins and mitigating price volatility. Moved to welfare gains, the use of DR will tend to displace the most expensive peaking units, reducing the system marginal cost [100]. If this reduction in generation came from fossil fuels, GHG emissions will decrease and cost related as well.

Moreover, if it is permitted, for instance Germany can Spain no, results from bidding can be negative, the reason is because is more expensive to stop producing than pay consumer for increase their consumption. This is a constraint difficult to applicate when modelling but ir implies economic benefits for consumers and growth of using DR.

RES penetration for or combined with DR participation leads to avoid or deferred **infrastructure costs**; less generation capacity is needed and even some elimination of it. Considering the state of the system, sometimes DR could therefore be cheaper.

Use of DR increases production system capacity but **capacity costs** from system operators are reduced, this can also be seen from the point of view of incentives for capacity that producers have. This “benefit” is difficult to evaluate as in some countries, incentives or capacity are about to disappear.

New actors in electricity market are expected to grow accompanied with **new business models**, services and products contributing to a more competitive and innovative environment, with more participants, especially in balancing markets [52].

Finally, participants can benefit economically because of diverse reasons: From incentive payments according to their pursuance on explicit DR programs and contracts and from lower energy bills savings. Lower energy bills come from reducing electricity usage during peak periods or from on-site generation substituting peaking power plants reducing peak prices.

RTP provides an **economic efficiency** with respect to flat rates. However, from the point of view of smaller customers is not as attractive as it is for larger customer according to proportional savings, expenditure on electricity represents only a small proportion of a typical household budget [101]. Residential loads are well seen for availability during many hours, but the greatest potential is related to industrial and commercial loads.

Planning benefits

DR reduces capacity requirements which entail a cost. DR reduces the need of expensive and sometimes inefficient investments. With DR environment, efficient plants could be used as base, with constant output generation and DR to meet wind generating fluctuations.

Rasmussen [102] defends that geographical diversity of DR could diminish congestion on transmission and distribution networks. Fortunately, whether or not congestion becomes an issue demand can be harnessed not only to avoid this additional congestion but also to maximize the utility of the network, thereby delaying or eliminating the need for **network upgrade and reinforcement**.

DR improve system reliability and reduce the need to enhance generation or transmission capacity [10]. Finally, efficiency gains in the form of capacity planning benefits are more important in long-term while in the short term are related to prices [103].

The new design of market performance will reduce the market power from big entities. Accordingly, consumers can have access to markets which increases competitiveness.

Environmental benefits

DR increases environmentally friendly generation with less GHG emissions for the same amount of energy generation (assuming that base units are RES or non-polluting

instead of coal units). After its implementation, DR brings on a better land utilization, air and water quality improvement due to increase of renewable resources and less traditional generating plants. Finally, it could also be observed a reduction of natural resources depletion.

In the future, once DR is fully integrated, less installed generation capacity will be needed to cover electricity demand. This result a more efficiency resource and a reduction of CO₂ emissions, because in most of cases peak units are highly polluting [52].

5.2 Challenges and barriers

Some barriers for the development of DR in Europe were seen last decades. Nowadays, some of these barriers can be later determined as challenges. Challenges arise from technologies available today and evolution of the market framework to reach the optimal use of data that is not developed yet. Changing market structure will be slow, as it implies a lot of work and is a long-term commitment [12].

In spite of Energy Efficiency Directive requirements, in Europe **little DR participation is available for small customers** who desire to access to day-ahead, intraday, and balancing or other markets. Normally, industrial customers have their own bilateral power purchasing agreements. These differences are mostly due to an incomplete regulatory environment in the majority of Member States and the lack of flexibility of electricity suppliers. Currently the amounts of responsive bid units that can bid are mostly for largest consumers. This participation is made with contracts between individual market stakeholders, direct market bidding planned many hours ahead or in emergency [47].

The lack of relation among electricity prices (based on the average electricity costs) and stresses caused on the grid do not translates grid issues to customers. The **low awareness of grid issues** does not incentive changing customers behaviour. As the money expended for electricity during a year is not seen as relevant by customers due to the interval payments, consumer uses electricity when needed, without prioritising to minimize the cost over the consumption, in this way, it is difficult to predict the economic impact due to uncertainty of market models.

The energy monitoring and **smart metering systems** introduced to the market should permit a faster and more comprehensive information regarding energy consumption and pricing [12]. But some smart meters may not be adequate to deliver all services required for DR and do not meet the standards across Europe. Many efforts from technologic and regulatory point of view are made in order to solve the issue but

still some work to do. Standardization of the communication interfaces is needed, to ensure fast enough transmit of the control signals between market players. Technical requirements of reserve and balancing power markets need solutions such as Home Energy Management System (HEMS) or Building Automation and Control System (BACS), as smart meters rollout have been already done and some other solutions should be meet [104]. Other solutions could be as Spring by Fortum has done: a single device permits the control, it acts as a virtual battery so that renewable energy can be consumed at an optimal time [105].

Barriers explained before are also related the lack of information for consumers about great impacts from DR and the **weak understanding of electricity markets** from most of the population. This information should be explained to customers. The derivate challenge is to provide the information to customers instead of be constantly controlled by the aggregators and elaborate policies to protect them from the data access of third parties as they have with traditional retailers, awareness of the situation could help to increase trustfulness on DR development [12].

Also, in many EU Member States is **not accepted by law to aggregate customers** like customers owning chains of buildings (supermarkets, hotels, public buildings, etc.) in order to act in wholesale, balancing, or capacity markets. Active mode of aggregation is limited because of high administrative and legal procedures that consumers have to meet [18].

Worse, some Member States have **more than one TSO** with different participation rules each. Insufficient standardized measurement and baseline methodologies that could compare the performance of DR implementation and motivate governments are seen as other barrier. Quantification of DR through smart metering and accurate measure changes would help the complex DR deployment among the European countries [106].

Consumer shares their load profile with a third party who has full **access to this data**. Retailers, DSO and BRP have this access, overpowering the system and impeding new entrants to participate in the market and customers to be rewarded for the value of their flexibility. In that way, defining DSOs' role is critical, more actively managed distribution network can give DSO excess power as they have access to metering data equal and fair access to DR participation should be promoted. This has recently been established in the Electricity Directive since some European countries do not. Additional concerns in reference of distribution of costs and benefits from flexibility between different consumer segments are also in debate if DSO uses DR [107].

Standardised regulation at the European level is a must, including clarified roles and responsibilities and a clear definition of the participants in the balancing market and permissions as well as the relationship between TSOs, DSOs and market operators [52]. These market definitions involve regulating the processes between the Balancing Responsible Party (BRP) and Aggregators and before permit their operation, markets must also establish attainable minimum trading volumes and also the non-acceptance of aggregated bids. Establishing an efficient market environment for DR is the principal challenge to face. The appropriate environment for DR englobes many changes on the legislative requirements and market mechanisms, redesign balancing markets structure and actors of the electricity chain to achieve a more competitive power market. Also is important to involve stakeholders setting clear rules and a standardized process [12]. After requiring for these needs, Electricity Directive and Regulation have recently been published covering the fundamental principles of these aspects. It would be necessary to see in the future how Member States execute these standardizations, and analyse which are the best and most viable applications.

Regarding the deployment of DR, **promote regulations concerning balanced budgets** to face upfront investments for DR across different Member States and publish their results could increase DR users. In the same line, networks tariffs and fees should encourage all participants equally, not favouring some industries. The tariff structures of the current network could create an unfair allocation of costs among users, particularly due to measurement restrictions that cause users to be on the same tariff despite creating different costs. As the number of "prosumers" increases, there may be an impact on network fees [108].

With DR, the **"responsibility" for maintaining system security** is shifted from the system operator to the end-user due to response made. However, this is necessary because TSOs are not allowed to own production or storage resources and they don't have demand either. For this reason, limitations should be made to avoid exploit end-users to provide system services as Zugno et al. [109] suggest. More suggestions were made as an extra payment to restrict the range over which prices vary, but for dynamic prices to succeed the price has to vary. On the other hand, if the prices not vary enough it may not worth it to respond to prices or even to recoup the cost of installation investment.

The **determination of the correct baseline** (consumption level without DR application) to compete with supply and other flexibility measures is very difficult to model. High numbers of assumptions need to be done when build a profitable business case due to lack of experience, especially at high temporal resolutions and at the level of

residential loads [6]. Even though researchers' focus is on social contexts such as policy, individual behaviour, education, and income level, in residential DR, simulate the demand curve is very difficult due to its dependence on other external factors. A better understanding of households' electricity usage could avoid to mislead conclusions [42]. Studies conclude contradictory behaviours between peak-hours and off-peaks hours, particularly it happens in the individual customer level. Customer behaviour does not reflect the economic behaviour expected in many cases.

When modelling DR in electricity markets, Oconnell et al. [7] observed three main assumptions that should be solved:

- *Economically rational demand behaviour*: electricity demand approach is not elastic, depends on diverse factors. It is necessary to solve the asymmetry response (the magnitude of the response to a high price may be different to the response to a low price).
- *Demand response as negative generation*: Among aggregated loads demand types behave differently, many different load types with many diverse operating characteristics and constraints which makes it uncertain.
- *Perfect knowledge of the system and demand*: scenarios predicted may not be representative, the characteristics of individual households and appliances would not be known by the power system operator.

Prices vary all over the time, but an issue with DR tariff schemes is the recreation of a shifted peak after low electricity price of valley hours. Differentiate the pricing also by regions, is what has been done in France to solve this new peak in other times; regions in France have different prices for DR in order to smooth loads in desirable ways [10].

To sum up, to evaluate benefits and challenges globally, it should be considered from stakeholders' point of view, a benefit for ones aren't for other or could even suppose a barrier. Some could lead to a conflict of interests as reflected on the following table:

	Benefits	Challenges
Aggregator	<ul style="list-style-type: none"> -Revenues from commercial agreements -Revenues from consulting services to final-users -Revenues from associated services -Minimal footprint capacity resource 	<ul style="list-style-type: none"> -Revision of market rules for balancing, reserves, capacity and wholesale market to include DR -Fair competition between market players -Define their role and responsibilities -Allow aggregation and flexibility service -Define the role and responsibilities
Balance Response Party	<ul style="list-style-type: none"> -Diversify balance sources -Improve their availability to provide balancing services -Increase revenues -Self-balancing 	<ul style="list-style-type: none"> -Need of more complex algorithms -ICT infrastructure and forecasting -DR potential knowledge
Retailers	<ul style="list-style-type: none"> -Offer new services to their end users and improve customer loyalty and satisfaction. -Portfolio optimization -Integration to balance management between procurement and sales -Novel products, pricing structures and business opportunities -Hedge against spot price volatility and uncertainty in their customers' loads -May provide services to DSO -portfolio optimization in case of risk hedging mechanism 	<ul style="list-style-type: none"> -ICT infrastructure and forecasting -Incentives for energy efficiency solutions -DR potential knowledge

DSO	<ul style="list-style-type: none"> -Limit peak power -DR as substitute for back-up lines -Optimise the uses of the network and -Grid infrastructure savings or delay or network reinforcements -Supply -Reliability enhancement 	<ul style="list-style-type: none"> -ICT infrastructure and forecasting -Incentives for energy efficiency solutions -DR potential knowledge
End-users	<ul style="list-style-type: none"> -Unlock and monetize their DR potential with their existing assets -Access to day-ahead and intraday markets -Electricity bills reduction by using dynamic prices or the other incentives and rewards given by DR -Optimise the size of the main fuse -Facilitates RES integration -Energy efficiency 	<ul style="list-style-type: none"> -Face social concern about batteries wear and tear -Standardized remuneration
TSO	<ul style="list-style-type: none"> -Cost reduction of balancing power market -Improves reliability and stability of the grid whilst reduces extreme marginal costs -coste reduction on frequency control in normal and disturbance situations -Cost reduction of taking actions in the different reserve power markets 	<ul style="list-style-type: none"> -ICT infrastructure and forecasting -Incentives for energy efficiency solutions -DR potential knowledge
electricity suppliers/ generation	<ul style="list-style-type: none"> available alternative solutions to source their power and avoid investing in peaking plants that operate for only a few hours per year, as well as globally improve the load factor of their assets Alternative source in case of unit outage Cost reduction of balance management in case of variable production 	

Policymakers	<ul style="list-style-type: none"> -Increases RES generators -Have functional energy markets which will lead to growing economies -Increase impact on network codes 	<ul style="list-style-type: none"> - Implement incentives according to EED -Having alignment between the National Energy Strategy and other policies -Standardised guidelines, granting non-discriminatory access to the markets to all users -Raising awareness on DR benefits -Accelerating the energy market development
Building Owner/ Manager	<ul style="list-style-type: none"> -Cost and energy savings -Improved operation of equipment -Green innovative image 	<ul style="list-style-type: none"> -Lack of interest -Complexity of system and expertise requires of flexibility/DR potential -Training needed for managers and staff -Uncertainty on future (dynamic) energy prices and regulations
BMS & equipment manufacturer	<ul style="list-style-type: none"> - Increase revenues -increase of sales of equipment and consultancy services 	<ul style="list-style-type: none"> -Knowledge of the state of energy demand, production and flexibility potential -Ability to accept and process DR signals -Ensuring comfort of the occupants -Interoperability between DR and management of the applications

Table 5. *Benefits and challenges from stakeholders point of view*

6. CRITERIA FOR DR ANALYSIS FOR TARGET COUNTRIES

This thesis is focused on the analysis of Europe and deeply in the five countries mentioned before: Finland, Spain, France, UK and the Netherlands.

Before analysing these target countries, is remarkable to have an idea of the situation. Implicit DR has achieved a favourable situation all around Europe with a variable prices option for consumer in most European countries. However, UK, Finland and France are the most active country regarding incentive-based (explicit) DR, and The Netherlands is expanding, while Spain has closed markets [5].

6.1 Criteria for implicit demand response

To achieve properly the implicit DR, smart meters should be largely deployed and useful, with adequate interfaces allowing data flow. Also, self-consumption helps to enable remarkable changes in consumption.

6.1.1 Self-consumption

The allowance of self-consumption empowers consumers in the electricity market, but is limited by regulation. Regulation considers self-consumption itself, connection supplements and network fees.

If self-consumption is not connected to grid and uses batteries to maximise the use of product it is locally possible and consumer can shift consumption more easily.

6.1.2 Revenues from load-shifting, peak clipping and self-consumption

This factor reflects the grade of accomplishment of implicit DR expectations. It depends directly from the available tariffs for load-shifting, peak clipping and self-consumption during the moments that are carried out.

When self-consumption is done, analyse which is its value, how and which are the revenues for participants from doing it. Also, it can be mentionable the difficulty to take advantage from self-consumption.

Moreover, net metering mechanisms are regulated already in some countries and their revenues need to be considered usually with explicit DR if it is allowed. Net metering will create differences between consumers due to transport tariffs applicable apart from the revenues of providing services to the power system, for example this was a problem until April 2019 when law in Spain was changed.

6.1.3 Smart meters deployment

This aspect aim is to examine the grade of the deployment of smart meters. Smart-meter are used as communication gateway to deliver DR control and for balance settlement

Tariff schemes of dynamic pricing are possible thanks to the extensive roll-out of smart meters, so it is important for consumers who want to participate in implicit DR to have one of them.

6.1.4 Type of tariffs available

There exist different ToU tariffs and RTP tariffs depending on the type of consumer, degree of commitment of the customer, country or even region where DR is offered. For all of them, particular dynamic pricing can be available and permit more users to shift loads from high electricity price to lower price.

6.2 Criteria for explicit demand response

The main reasons for DR application around Europe are national and regional legislations that keep off or incentivize DR. The most innovative applications of and studies Explicit DR are related to balancing and ancillary services.

Based on literature seen in “Explicit demand response in Europe, SEDC” and some other information about the grade of current application of the EED criteria for the deep analysis is as follows:

6.2.1 DR access to markets and aggregation

This aspect is the most related to the grade of application of EED, particularly Art 15 [110]. It includes the analysis of basic conditions for DR application and enables aggregation.

Issues in Member States that allow aggregation state on the encompassment of roles and responsibilities of aggregation sellers, where only retailers can be aggrega-

tors. Clarify the relationship between retailers, independent aggregators and BRPs and the roles which have to accomplish facilitates the access of new entrants to the electricity market working towards a more competitive one.

Also, technical discrimination referred to the voltage level of connecting point, the maximum level of reserve provided and the priority given to participants is interesting to mention. Other factors to face are the interoperability among DSOs, this refers to the availability of the aggregator to have agreements with different DSOs. This could be applicable for example in case of distribution grid congestion, emphasizing EV application, because of their availability of geographical changes.

In new markets design, all participants should compete for their own benefits without modify other participants strategies.

6.2.2 Service provider access to markets

Service providers and market options should be diverse and consumers who want to take advantage of their flexibility should choose freely between the options, retailers should not be part of this election.

If aggregation is approved, the aggregation service providers must be able to operate independently from the consumer's BRP/retailer, which interferes in aggregators' business model and blocks their market entry. DR should grow in a healthy competition environment between market actors.

Four standardised elements must be incorporated to assure free consumers' choice. These are:

- Standardised processes for assessment of the traded energy and its volume
- Fair compensation for the retailer and consumer/aggregator due to losses caused by changes between estimated and real users' patterns
- Limit as much as possible data exchange among BRP, aggregator and TSO to increase the privacy of the parts and reduce fear
- Precise structure defining the roles and responsibilities: who and how responds in case of a problem

There are several service providers. For instance, REstore is a "virtual" service supported via IT platforms that facilitates DR participation around Europe, whereas others such EnerNOC offer consultancy services in the form of technical and design advices and business modelling. Also, important tasks are made by Energy Pool which works in France, Belgium and UK implementing DR programs.

6.2.3 Participants requirements

Energy transition has no sense without changing product/programs requirements. Reigning systems' performance blocks low-cost demand-side resources, and hence inflates procurement costs. Reduce costs form the power system towards a more efficient and environmentally friendly way is a current need of the systems. Markets should be designed in a granular manner, in order to enable the full range of resources to enter [5].

Criteria for product configuration analysis come out from answering who, how, how much and when DR is applied. Result of these participants' requirements is focused on the seven elements below:

- Grade of competitiveness framework, transparent market encourages to participate which in turn competitive increases
- Minimum power amount for a bid, realistic amounts encourage new entrants for DR
- Length or availability required to be able to access to the market. As shorter durations requirements the merrier.
- How long in advance of delivery the procurement of reserve is made, because assumptions and uncertainties vary with time.
- Allowance of asymmetric bidding, most consumers cannot control in the same amount up or down consumption amount. Asymmetric bidding could help to optimise the use of the resources of DR.
- Is there required real-time monitoring of DR resources?
- How deterministic the DR response need to be?

Besides, all steps to meet systems' necessities need to have in mind new technologies penetration and consider the benefits that it provides.

6.2.4 Measurement and verification, payments and penalties

Legalising DR in each country is only one of the sundry steps that should be made. To ensure a strong development of DR, designing a reliable baseline methodology is a must. Moreover, optimise communication among loads/generation and paying providers is other interesting aspect to analyse.

Understanding baseline as a reference what consumer would have been consumed without DR or an estimation of that. Fair and transparent baseline model permits consumers to estimate their variation and consequently the amount that they could be paid changing their electricity usage patterns. For this reason, the best approach of base-

lines considering different factors as time, amount of consumption, degree of commitment of consumer should be publicly available and revisable at least once a year.

When aggregation is allowed, defined pre-qualification, measurement and verification are needed. Communication between the parts (system operator and aggregator) has also to be defined, having in mind the individual consumer welfare.

There exist different schemes to remunerate reserve: Regulated tariffs, pay-as-bid, and uniform pricing [21]. For aggregation, all of them have their disadvantages. Regulated tariffs do not reflect the continuous fluctuation of prices in the spot market. While between the other two options, as pay-as-bid is based on what the player expects and aggregators are new entrants to market, they have less information about the market.

In reference to finance and penalties, healthy payments criteria, volume and values according to flexibility are essential. The correct principle payment to market participants is Pay as Cleared (PAC), as stated within the European Network Codes. Clearness of penalties of non-delivery DR is also imperative to be examined. Penalties should not favour one source over others, they need to be differentiated depending on the market and the risk posed.

7. DEEPEN ANALYSIS OF TARGET COUNTRIES

An overview of DR situation in the target countries is being presented in this section. Every year more and more investment in smart grid R&D and demonstration are done in Europe. Differences on the level of investment in each country depend on national policies, the state of the electricity grids, the regulatory framework, the existence and scope of co-funding mechanisms at national and European level. Demand-side management (Demand Response and Energy Efficiency) investment in Europe is around 25 % of the total European investment in smart grid R&D [111] . Joint Research Centre (JRC) outlook report [111] set in order the actors relevance in this investment, principally made by DSOs and followed by ICT companies, universities and technology manufacturers but also by producers, BRPs and retailers.

According to a 2015 study by Sia Partners, the total DR potential in Europe amounts to 52.35 GW: 42% from residential applications, 31% from industry and 27% from the tertiary sector (mainly HVAC and commercial refrigeration) [112].

Pilot projects in real-life conditions are crucial for the learning required for market deployment of innovative technologies like DR solutions and practices, for this reason a specific subchapter is done for each country. Also, pilot project alleviates users' concerns about operational risks. Several countries are establishing smart meters and data exchange platforms or data hubs to facilitate the data collection, storage and exchange on a national level; France and The Netherlands are good examples of running this type of applications.

7.1 Finland

Finnish electricity market is part of the Nordic electricity market, NordPool. Finland joined to this deregulated electricity market in 1998. Nordic countries (Norway, Finland, Sweden and Denmark) have separate TSOs, though they share a single electricity market. In Finland, the transmission system operator is Fingrid. Referring to regulation among these Nordic countries, there exist differences. Regulation is based on the national laws of these countries although the aim is to harmonize them from the national level, which includes DR and aggregation regulations.

Major part of the wholesale trade in electricity takes place in the Nord Pool Spot power exchange. Elspot (day-ahead) and Elbas (intraday) markets set the market price for electricity in the Nordic countries. Distribution networks are owned by regional and local energy companies, public parties and private domestic and foreign investors [113].

Almost all Finnish legislation related to the electricity sector is included in the Electricity Market Act (588/2013,EMA) [114] and Decrees and Orders based on it. The EMA, which entered into force on the 1 September 2013, implemented the EU's third Energy Package and more important related to this thesis, the EED principles [74].

Shortly after, in spring 2014, the EMA was adjusted to stipulate that tariffs cannot provoke a decrease of an overall efficiency of electricity generation, transmission, distribution and supply or motivations which endanger DR application [115]. Provisions on incentives used in the terms and conditions and pricing (tariffs) of system services are laid down in sections 24 a) and 24 b) of the EMA.

The Finnish National Energy Efficiency Action Plan (NEEAP) [115] expounds that Finland has already implemented some measures listed in paragraph 3 of Annex XI of the EED. These measures are related to clauses ToU tariffs and real-time pricing.

According to section 53 a) of the EMA, DSOs shall have general and easily applicable procedures for connecting small-scale electricity production referred to in the EED to the distribution system.

At the end of 2016, Finnish government promoted DR, with special attention to market-based DR, by creating a working group with the aim of enable the easy participation of consumers in the electricity markets and clarify the roles of operators.

Fingrid obligation reserves in 2017 were [116]:

- About 140 MW for FCR-N
- 200-265 MW for FCR-D
- 70 MW for aFRR used in certain morning and evening hours
- 880-1100 MW for mFRR

7.1.1 Implicit DR

The Nordic regions have focused on enabling implicit DR through smart meters' rollout and dynamic tariffs. Decree 66/2009 requires DSOs to implement smart meters all around the country by the end of 2013. Furthermore, according to this decree, meter has to register hourly electricity consumption, and "the metering equipment shall be

capable of receiving and executing or forwarding load control commands sent through the data transmission network” [117]. Currently, the installation of smart meters has reach over the 99% of consumption places [118]. This smart meters rollout allows retailers and DSOs to offer more sophisticated tariffs because are remote readable, register hourly consumption data, and have some load control functionalities [104]. Finland has two tariff systems: retailer and DSO has their own tariffs.

Finland initiated in the 1970s time of use tariffs when electric heating was introduced to domestic customers. ToU tariff were offered by most retailers and used by around 1% of households and 85% residential customers with electric heating [119]. RTP has been offered by retailers since 2010, after the introduction of smart meters. RTP is based on NordPool market and communicated to households. There is not public data but it is estimated than less than 1% of households [119]. Nowadays, Finnish companies are studying which is the best option to control, in every moment, the flexibility consumption available for markets. Also in Finland there are Power grid tariffs which help to reduce peak demand.

The next generation of the meters will bring ICT and Smart Grid technologies closer together which will enable entirely new functionalities. *Landis+Gyr, Aidon* [120] are developing them in Finland [78].

There exist many business models for RTP with home automation devices in Finland [119]. Home automation can be also based in ancillary services. Basically, the home automation device receives the price signal from the retailer, based on the day-ahead spot market, and optimizes the use of the associated energy appliances which have some kind of storage capability like space heating, hot water, cooling systems....

Automation options are currently being developed and deployed in limited areas, such as the Helsinki region to allow consumer react in actual time thanks to technology and some form of business/home automation. Vattenfall and Fortum [121] are working to develop a viable business model but it is being difficult.

Regarding implicit DR in Finland, self-consumption is made with low revenues for participants. In spite of having a high deployment of smart meters there are not available high variety of tariffs.

7.1.2 Explicit DR

The markets available to Finnish DR are the energy market NordPool, the reserve markets operated by Fingrid and the capacity market operated by the Finnish regulator (Energiavirasto).

Finnish Regulation does not define a role for independent aggregators; however, it allows prequalification for participating in a market performed at the aggregated pool level, rather than for each consumer individually. Retail consumers can participate in wholesale marketplaces, by offering DR through aggregators. Also, access to ancillary services markets offered by retailers, is allowed in diverse degrees through supply contracts within the Nordic Spot Market and national balancing and reserve markets.

In spite of that, some limitations still to be addressed, aggregators and BRP bilateral agreements have some impediments that have to improve. In the aggregation situation, one load can be only aggregated to a one BRP area; the aggregator cannot choose the BRP according to conveniences of both. Hence, consumer is not able to choose freely his service provider because retailers/BRP decides under which conditions and with whom they engage an aggregator.

The definition of aggregation in the Nordic regulation tries not to change the market structure, costs and benefits should be proportional to parts participating, which in turn, is not exclusively focused on permit consumers' access to DR/service providers. These services are given by retailers which have difficulties to design a positive business case as they also have different incentives than consumers/aggregators for market entry. Independent aggregator without balance responsibility may create huge trouble for retailers, producers and BRPs which are responsible of keeping balance. At least the independent aggregator would need to compensate these costs to other stakeholders.

Law in Finland permits all products for DR under some requests. Aggregators operate in the frequency control, in the tertiary reserve and in the spot market, while only pilot projects are underway in the secondary (aFRR) and primary frequency reserve (FCR). This lack of exploiting the full potential of DR is mostly caused because of the large minimum bid size for some products.

Fingrid is the instigator of DR in Finland making progress optimising DR capabilities for the ancillary services market and has also contracts with the largest industrial consumers to provide emergency reserves. The main aggregators that operate in the balancing market are resource owners in the FCR-D reserve. DR current contractual arrangements for strategic reserves decided by the regulator are two DR units; two heat pumps of 10 MW and 12 MW each [118].

The TSO has worked actively with national consumers (household to industrial) to enable participation. Markets places with their corresponded type of contracts and size bids as well as the market gate closure and the activation time of the services and the respective price in 2018 is available in Fingrid webpage and can be seen in Table 9:

Market place	Type of contract	Minimum bid size	Market gate closure (EET)	Activation time	How often activated	Price level in 2018
Frequency controlled normal operation reserve	Yearly and hourly markets	0,1 MW	Yearly market previous autumn, hourly market day before at 18:30	3 minutes	Several times a day	14 €/MW,h (yearly market)
Frequency controlled disturbance reserve (FCR-D)	Yearly and hourly markets	1 MW	Yearly market previous autumn, hourly market day before at 18:30	Partly or full linearly within 5 s / 50 % and 30 s /100 %, when f under 49,9 Hz or single step activation 5 s when f under 49,7 Hz 3 s when f under 49,6 Hz 1 s when f under 49,5 Hz	Several times per day - per year	2,8 €/MW,h (yearly market)
aFRR	Hourly market	5 MW	Day before at 17:00	Must begin within 30 s of the signal's reception, must be fully activated in 2 minutes	Several times a day	Hourly market ² price + balancing energy price
Balancing power market (mFRR)	Hourly market	5 MW	45 min before each hour	15 minutes	According to the bids, several times per day/per year	Market price ²
Balancing capacity market (mFRR)	Weekly auctions	5 MW	Week before on Tuesday at 12:00	15 minutes	According to the bids, several times per day - per year	~3 €/MW,h
Day ahead market	Hourly market	0,1 MW	Day before at 13:00	-	-	Market price ²
Intraday market	Hourly market	0,1 MW	30 min before each hour	-	-	Market price ²
Strategic reserves	Long-term contract	10 MW		15 minutes for DSR, 12 h for power plants	Rarely"	-

Table 6. Markets places of DR in Finland [122]

² Market Price corresponds to the market place price of each case in real time.

From analysing the Finland economic profitability of DR, [104] concludes that resources have higher economic benefits when used in reserve and balancing power markets instead of in the day-ahead markets. Conclusions from this study could be further analysed as it does not consider self-balancing of BRPs for example. Considering that all traded bids will be accepted does not reflect reality in reserves or balancing power markets. Therefore, amount of trading volumes are important from aggregators viewpoint, is not the same small gain per unit when small or large amounts are traded.

DR consumers in Finland typically consist of large industrial consumers (forest and chemicals industry), and partly small industrial consumers/services (e.g., supermarkets and households). Due to large amounts of electric heating, Finland has high market volumes for DR. Only pilots exist in small-scale for reserve and balancing markets. However, lately there is an increasing trend in Finland in favour of business models for DR, covering most offerings in some reserve products and small-scale participation through aggregation. Enspirion, Seam [123], and Energia Kolmio are the major DR aggregators in the country.

In reference to explicit DR, It can be concluded that Finland is very developed. All markets are accessible and aggregation is allowed. The problem is on the inexistence of independent aggregator role definition. In spite of that, participants' requirements are strict for the amount of bids, which are high but asymmetrical bidding is permitted. Prequalification is at aggregation level, payments are unattractive and also penalties are applied.

7.1.3 Finnish pilots

As said, Finland is the most developed country in Europe in reference to flexibility. This statement could be influenced by the significant seasonal variations in heat and electricity demand [119]. Many university researchers analyse the advances made by Finnish DR and the stakeholders opinions to facilitate to tackle the existing barriers; one example is [117].

Already in 2014, *Seam Group* and *Fingrid* worked for integration of residential and commercial loads in the reserve markets, concretely, the pilot intention was to add a frozen warehouse in FCR-N market [124]. After its implementation, was agreed that refrigeration devices, vaporisers and condensers are appropriated to operate as FCR-N.

On the other hand, the energy company *Helen Ltd* offers a contract based on hourly spot price plus a retailer margin to all residential end-users excepting the ones with

specific control heating which are used as load in their VPP in the reserve markets [118].

Fortum is another company investigating for DR; it announced that with the collaboration of one thousand of its residential water heater customers has created a one-megawatt virtual battery operated by Fingrid in the FCR-N markets.

Helen also made some steps in reference to DR in the commercial and industrial sector. Since 2016, Yandex data center is utilized as a part of a VPP in the FCR-D market. Yandex data center energy consumption is equivalent to 3500 households consumption [118].

Other commercial pilot taking place belongs to a grocery stores company, *S-Group*. S-Group already in 2011 pre-piloted one large department store and two grocery supermarkets with incentive based DR [125]. From 2015 to April 2018 the S-Group also ran a case of study with the peculiarity refrigeration equipment as energy storage and energy resources (photovoltaics and ground heat) integration in DR. This last pilot demonstrates that DR capacity is great even in high energy efficient systems but it also alludes to the unsuitability of current reserve and balancing markets for small aggregated loads.

Also, is mentionable Siemens project [126] in the commercial centre “Sello” which considers data from HVAC systems, air quality and temperature sensors, occupancy rates and weather optimises the energy efficiency. Sello’s microgrid combines energy efficiency, storage, optimization of peak loads, and its own electricity production and has been able to supply the extra energy to the reserve market leading to an income of around 650,000 euros annually for “Sello” property owners. With this successful project, Siemens Finland is expanding its VPP business model under the name [127]

Nowadays, Fingrid is working jointly with *Helen* and the French aggregator *Voltagis* with some pilot projects that aim to include independent aggregators in the balancing power markets [128].

Kalatasama is a big pilot project which reaches the categorization of smart city. The pilot includes smart power grid with local production of renewable energy, infrastructure for electric vehicles, energy storage, energy-efficient building automation and DR management [129].

A Mentionable pilot is Flex4grid pilot which in a first moment, was implemented in Germany, but due to lack German deployment of smart meters, VTT accepted to extend the pilot with users in Oulu, Finland. The goal is to distribute Extended-kits

(Flex4Grid gateway, five smart plugs and further accessory) to 70 prosumers in Finland [130]. The project aims to develop an open data and service framework for prosumer flexibility management, thus offering new services to DSOs, prosumers and third market players.

Last but not least is a recent case of study in Finland is the optimization objectives of the network (efficient use for DSO) and market-based (economic benefits for retailers) DR. The idea of the study arises from the conflicting interests between DSOs and retailers. Results show that network-based DR benefits increase much faster than market-based DR benefits when load control potential is increased. This supports and approach that focuses primarily on network-based DR, using the residual load control potential for market based DR [131].

More flexible projects in Finland within the European H2020 budget project are: DOMINOES (micro grid site in Lappeenranta) [132], HEILA (Integrated business platform of distributed energy resources), and DIGI-USER [133] are carried out. Furthermore, solutions are under testing in various pilot sites, such as LUT LVDC [134] micro grid.

7.2 Spain

Spanish structure for the electricity sector is regulated. The government is responsible for establishing network remuneration methods, while the National Markets and Competition Commission (CNMC) is responsible for establishing a methodology for the allocation of costs of access taking into account the remuneration of such activities [135].

Referring to large electricity consumers, last NEEAP available indicates that some measures to regulate competition mechanisms for the allocation of interruptibility demand management service have been taken with the approval of two orders [136]. Measures to deploy DR participation in small consumers were considered in Law 24/2013 of the Electricity Sector and in the Royal Decree (RD) 216/2014 [74]. RD 900/2015 introduced the slow transition towards a distributed electricity-generation model considering small-scale systems; this RD has brought many issues regarding self-consumption.

The "*Código de la Energía Eléctrica*" [137] orders and compiles all the regulation of the Spanish electricity sector. The document is permanently updated with the changes and accessible to the public. The constant evolution of the electricity sector is reflected in this document. Relevant rules about this thesis topic are:

- RD 661/2007, which regulates special regime electricity production.
- Order IET 346/2014, amending the Order IET / 2013/2013, by which the competitive allocation mechanism management service demand interruptibility is regulated.
- RD 216/2014, which clarifies the methodology for calculating volunteers' prices for small electricity consumers and its legal procurement regime, is established.
- RD 56/2016, February 12th, which transposes the EED regarding energy audits, accreditation of service providers and energy auditors and promoting efficiency of energy supply.
- RD 900/2015, by which the administrative, technical and economic conditions, of electric energy supply modalities with self-consumption are regulated [138].
- RD 15/2018 eliminated the so-called sun tax to provide certainty for energy 'prosumers'. The regulations define different types of self-consumption including collective self-consumption and communal self-consumption. Also, this regulation simplifies mechanism's payment for any surplus energy injected back into the grid.

Currently, in Spain, flexible generation mostly comes from hydropower and gas but due to high renewable resources installations, more flexibility is needed. For the moment, it is compulsory for renewable generation units of installed capacity above 10 MW to be connected to the renewable network control centre called CECRE. Separate metering is required for any installed capacity while net metering is not allowed.

7.2.1 Implicit DR

Full smart meter roll-out is expected to be completed the current year. To date, in Spain, all consumers having a smart meter installed can sign a contract with the retailer with hourly tariffs.

First tariff in Spain with hourly discrimination was night rate tariff. This tariff applied a discount of 55% on consumption made in an 8-hour stretch at night, and had a surcharge of 3% during the rest of the day. This rate was intended for users with electric heating systems and hot water since installing electricity accumulators that worked at night they got a significant discount on the price of electricity.

In July 2008, night tariff changed the night rate to the new rate with time discrimination, with wider valley hours and less discount rate the ones before. In contrast, the

surcharge that is applied in the rest of the hours of the day increases to approximately 30%. That changes and hours of its application can be seen in Table 7:

	Number of hours	Discount (-) or surcharge (+)	Application timetable
Valley hours	14 hours/day	-40% aprox.	Winter: from 22h to 12h Summer: from 23h to 13h
Peak hours	10 hours/day	+30% aprox.	Winter: from 12h to 22h Summer: from 13h to 23h

Table 7. First ToU tariffs in Spain

In order to incentivize EV, in July 2011 a new tariff was created, the *supervalley* which divides the day in one more period [139] as can be seen in table below:

	Number of hours	Discount (-) or surcharge (+)	Application schedule
Supervalley hours	6 hours/day	-55% aprox.	From 1h to 7h
Valley hours	8 hours/day	-30% aprox.	From 23h to 1h and from 7h to 13h
Peak hours	10 hours/day	+30% aprox.	From 13h to 23h

Table 8. Current ToU tariffs in Spain

The voluntary Price to the small consumer (*Precio Voluntario al Pequeño Consumidor, PVPC*) is how is called the hourly basis tariff in Spain. This tariff is applied to households with less than 10 kW of hired power. There exists a different price for each hour of the day, consequently during the day there are 24 different prices. These prices are imposed by the Spanish Industry Ministry according to the wholesale market. Then the Spanish TSO, *REE* published them at 20:30 on the day-ahead to allow consumer to organize their consumption for the next day. This information is publicly available in [140]. A comparison of tariffs offered by retailers can be found in [139].

Recent change of law that has eliminated the “sun tax” could change the overview in implicit DR in Spain. Nowadays, self-consumption is not commonly used and there

aren't revenues are very low. Smart meters are widely implemented but not used properly because of low use of ToU tariffs by end-customers.

7.2.2 Explicit DR

In spite of the existence of some smart grid pilot projects in Spain, Explicit DR is yet to start. Aggregation is illegal in the Spanish electricity system. The unique scheme that allows Explicit DR is the Interruptible Load programme.

Interruptible Load programme is used by large Industrial electricity consumers like construction industries, material factories (chemistry, paper...) or desalinization plants connected to the high voltage grid. The programme is managed by the TSO, "*Red Eléctrica de España*" (REE) and intervenes in extreme limits of grid operation, when the system needs generation and balance resources are not enough these large consumers reduce their demand. It is remarkable to mention that this program has not been called for many years. That program has not be understood as load shedding, because in this case consumer is asked first which in turn is voluntary and they are paid for the service [141].

To participate in the program mentioned before, consumers need an ICT system linked directly to the TSO, not to the DSO with which maybe is connected. DSO does not participate in the program, TSO receives the retailer's imbalance and it directly corrects it sending a reduction order. The baseline is set individually and the available capacity is tested around twice a year. Participants send monthly two months forecast to the TSO.

In residential sector, the lack of penetration of consumers to flexibility services in balancing markets is caused by the low frequency of meter readings among other factors. First step towards opening the market is the very recent RD 15/2018 for self-consumption.

Moreover, production unit seller in the wholesale market has to be bigger than 50 MW. In the spot market, flexible resources can participate though demand bids indicating the price.

Any of criteria can be analysed in Spain as it is forbidden to realise explicit DR.

7.2.3 Spanish pilots

A. Conchado et al. [142] analyse the potential benefits if DR is applied in Spanish households, the author focuses the benefits especially for DSO and generation parts.

In reference to the baseline taken, generation system benefits are higher than distribution system due to economic savings in fuel and emissions.

Already in 2010, during 4 years, *Gestión Activa de la Demanda (GAD)* Project [143] tried to determinate the barriers, benefits and needs to tackle in the future to implement DR in the residential level according to the Spanish electricity market situation from that time. From data of consumers, questionnaires about their availability and the implicit tariffs existing, they evaluated the viability of DR deployment in Spain and the needs to take by policy makers.

Generally, Flexiciency project aim is to develop DSO platforms enabling: provision of metering data close to real time to any interested stakeholder, data storage, data analytic and forecasting and technical validation of requested services. Flexiciency project in Spain takes place in the city of Málaga. The information about the performance of devices can be consulted in [144]. The pilot tests three main types of services:

- Energy monitoring services by providing advanced information and alert final users,
- energy control services from electric vehicle charging stations, storage and renewable generators,
- flexibility services in terms of power control, and voltage and frequency quality provided to the DSO by the service provider in a microgrid.

There is a lack of transparency in Spanish pilots, Spanish companies, normally, do not publish their improvements or projects until they are already implemented.

7.3 United Kingdom

The transmission system in UK is run by National Grid. In UK, the electricity and gas markets are regulated by the Gas and Electricity Markets Authority (GEMA) which delegates its functions to the Office of Gas and Electricity Markets (Ofgem).

UK NEEAP only mentions that transmission and distribution tariffs do not prevent suppliers from improving consumer participation in achieving DR development [74].

RIIO (Revenue=Incentives+Innovation+Outputs) ED1 is Ofgem's performance-based framework to set the electricity price controls. The RIIO model encourages network companies plan a long-term strategy for delivering network services to their customers. RIIO guide [145] make an approach to flexibility of network systems, including DR.

Also, Ofgem has a Third Parties Intermediaries (TPI) Programme which considers the enduring long-term regulatory framework for TPIs and consider regulatory measures to some energy retail markets covering household and business consumers.

In 2016, UK Government jointly with the National Regulatory Authority publicized a wide number of recommendations to establish DR potential, storage and other smart grid technologies so as to increase efficiency and flexibility of the electricity system. For that, the UK Government committed to allocate at least £50 million for innovation in smart systems form 2016-2021 [146].

7.3.1 Implicit DR

The UK Government is committed to ensuring that every home and small business is offered a smart meter by the end of 2020 [146]. A research on ToU tariffs in UK [147] concludes that around 30 % of British people would change their electricity tariff to static ToU tariff.

Thanks to smart meters “world-first” ToU dynamic tariff was introduced in June 2018. Octopus Energy developed this Smart ToU tariff, called Agile Octopus [148] which is Britain’s first half-hourly time of use tariff for households, which prices reflect the actual changes in wholesale electricity prices.

UK energy suppliers OVO, Octopus, Scottish Power, Eon, and Ecotricity have all launched tariffs designed for EV drivers. Green Energy became the first UK energy supplier to offer a static ToU tariff in early 2017, offering its smart meter customers a much cheaper rate of electricity during weekday nights (11pm-6am).

In UK, industrial consumers forecasting of peak demand periods and their management of injection/withdrawals during the periods are very well paid. On top of that, industrial and large commercial users can agree ToU or interruptible contracts with suppliers [149]. Likewise, the TSO, can contract directly such large users for balancing activities.

The *Triade Charges* allow consumers to earn off of flexibility; they can reduce their energy charges by reducing consumption over peak periods. Half-Hourly settled meters within the UK pay a levy set by the TSO based on each meter's usage during the highest three half-hour periods of demand on the transmission networks. Service providers may send triad warnings to their customers about 20-30 times annually, up to one day in advance in order to warn them of a possible peak triad period. This program has also its benefit on the congestion management of the network [150].

Implicit DR in UK is high developed. Self-consumption is widely used as well as revenues are high. As in Spain, they have wide deployment of smartmeters but only a few varieties of tariffs are available.

7.3.2 Explicit DR

Frost & Sullivan, through its analysis [28], gathers that 80% of the customers engage in DR programs through an aggregator, 20% contract directly with the National Grid, and the rest 10% through their DSO .

Great Britain has started to deploy “new generation” smart meters, which are able to meet the minimum frequency target to enable consumer participation in balancing markets [151]. Among the countries analysed in this thesis, Great Britain is the only country where electricity retailers are the responsible for the smart meter roll out [152].

UK was the first country in Europe to open sundry of its markets to consumer participation. Currently, aggregated load is accepted and all balancing service markets are open to DR, but there appear entry barriers in most markets. As a result, the evolution has not been as forecasted, some measurement, baseline, bidding and many other procedural and operational requirements are still inappropriate for DR growth.

Any party “supplying” electricity to a third-party consumer is required to be licensed by Ofgem. The license then places obligations on parties to accede to the relevant industry codes, such as the Balancing and Settlement Code.

Nevertheless, the aggregator is not required to contact the retailer/BRP directly and ask for permission to load curtailment; this lack of clarity of relationship is an issue that is not yet resolved. Independent aggregators can directly access consumers for ancillary services and capacity products and may aggregate load from all over the country [5]. Aggregated DR in capacity mechanisms is allowed but the rules are very restrictive and favour generation units. Conversely, the wholesale markets remain closed to independent aggregators [5].

The consumer is contractually obliged to inform the retailer its intention to participate in the market. Rules need to be formalised and legislation introduced to allow third-party aggregation participation while protecting the retailer/BRP from sourcing losses and imbalance payments caused by a third-party aggregator. Currently, large industrial customers and retailers carry out DR with directly participation in day-ahead and intra-day markets.

Concerning BRP’s imbalances caused by load curtailment, the customer has no obligation to maintain a consumption profile. Due to low affected retailers and few partici-

pation of DR, Ofgem do not consider urgent to elaborate an adjustment mechanism to control the issue.

In UK, numerous DR programs are offered by National Grid such as Short-Term Operating Reserve (STOR) and in frequency response. Also, National Grid makes recommendations to organizations for market access. STOR requires 11-13 hours per day (on weekdays) participation or to choose one-time window (morning/evening), but it involves high decrement of revenues [153]. Moreover, *Kiwi Power* Company like in other many countries has implemented frequency response, capacity reserves programmes and Network constraints management.

National Grid is based on large producers' mandatory provision for reserves and firm frequency response (FFR) that allow them to participate in the market. The participants are able to bid each month to provide different services for only one part of the day (different for weekdays, Saturdays and Sundays) without changing the amount of reserve provided.

Regarding product requirements, all products are asymmetrical with a minimum bid of 10 MW. To participate, provision of reserve with FFR must be cheaper than mandatory provision, but as there are more than 20 parameters procurement and selection optimisation, there could be some errors. Aggregators with less volume than 10 MW can participate within FFR bridging contract which lasts one or two years with regulated remuneration and proportional to the MWs aggregated. The payment rates are not public.

To sum up, in UK all markets are not opened yet, wholesale markets remain closed. Aggregation is allowed but there is a lack of clarity between aggregators and retailers relationship. When accessing to opened markets, they have high minimum bid sizes requirements and need to be symmetrical. Payments are correct because are proportional to the MW shared.

7.3.3 UK pilots

In 2004, Flexitricity apart from provide generation (small hydro and stand-by generators), it started to operate as large industrial and commercial load (more than 50kW) aggregator. It can incentivize clients for upward and downward load management and eventually trade this flexibility in markets or supplying balancing services such as STOR service [10]. Flexitricity's aggregation programs do not incur any cost; the company is responsible for installing the communication, metering, and control equipment. Furthermore, DR is used for triad management.

In December 2013, Demand Side Balancing Reserve (DSBR) and Supplemental Balancing Reserve (SBR) were implemented for balancing purposes. The reserves markets were carried out by National Grid with the approval of the Authority Ofgem. DSBR participation is for voluntary large energy users who diminish their demand during winter weekday evenings between 4 and 8 pm in return for a payment. SBR is closer to DR but it was seen that these services did not facilitate capacity markets. These services were removed in 2017/2018 because they were not needed, lack of market intelligence and customer's support was seen also as an issue for its application [154].

From August 2018, exceptionally, small generators can access to the balancing market on a minute-by-minute basis thanks to Limejump service. This is an industry first made possible through a derogation issued by Ofgem. ENTSO-E projects, as TERRE, MARI and PICASSO will open up the balancing market to a wider range of flexibility providers, which should drive down costs to the end, for this reason the service was allowed by the Ofgem [155].

Six DSOs in UK have joined to Piclo Flex. The platform creates an independent marketplace which allows meeting DSOs and flexibility providers and agreeing a contract between them. DER can detect flexibility necessities through a dashboard, pre-qualify assets, and be notified from relevant auction [156]. In the pilot, participated 175 flexibility providers with a total combined capacity of 4GW contributing to the management of local grids in congested areas. In May 2019 they signed their first commercial contract with *Scottish and Southern Electricity Networks (SSEN)* [157].

OVO Energy and Nissan are working on a domestic vehicle-to-grid demonstrator. The project is currently taking place and will involve 1,000 households using OVO's grid balancing platform 'VCharge' to support electricity grid balancing.

In October 2017, E. ON commissioned a 10MW lithium-ion battery at a biomass combined heat and power (CHP) plant near Sheffield. The battery provides Enhanced Frequency Response to the Electricity System Operator, responding in less than one second by exporting or importing power to keep the frequency of electricity flows on the grid at an efficient and safe level [158].

Transitional Arrangements (TA) auction is a pilot which forms part of Capacity Market with the aim of encouraging DR growth [159]. The first TA secured 803 MW of capacity for delivery in 2016/17, and the second and final TA secured a further 312 MW of turn-down DSR for delivery in 2017/18 [146]. The lower volume at the second auction is because it was also open to back-up generation behind the meter and to small-

scale, distribution connected generation. It is remarkable the high volume of DR in capacity securing agreements in the latest four-year ahead auction is 1.4GW of DR.

7.4 France

France is one of the most forward thinking and active markets in EU for DR. French TSO, RTE (Réseau de Transport d'Electricité) actively develops the DR market in the country, creating a regulated and a standardized framework and designing the market to be more aggregation-friendly considering all parts involved.

French NEEAP does not mention Art 15 from the EED. It only mentions some initiatives for Smart Grids [74].

Rules are described and issued by RTE. Every day, RTE notifies producers the reserve they must provide to the system for the next day scheduled every 30 minutes based on individual generation schedules. One barrier is discrimination between conventional generators and renewable energy, which in turn affect DR. For conventional generators provide primary and secondary reserves are mandatory and are remunerated while renewable generation do not participate. Renewable resources also meet some differences in wholesale market access compared to conventional generators.

Last years, to allow prosumption, rules have evolved. Production units can provide asymmetrical bidding but the amount of reserve needs to be at least 1 MW. Prosumers remuneration is regulated in the same way as mandatory provision but in 2016 was established a maximum of 40 MW of this type of provision reserves [25]. The evolving national legal framework is as follows:

- Since “Nome” law of December 2010, TSO is allowed to contract DR capacity. Its application result has caused in 2016, up to 1900 MW from industrial customers and up to 200 MW for residential DR.
- Recommendations of the Competition authority in 2012 and 2013: the BRP and the independent BSP are competitors and cannot be required to sign an agreement when the BSP values flexibility for a consumer.
- “Brottes” law of April 2013 gives a clear framework for the valuation of DR on energy market: no prior agreement of the retailer/BRP required for Independent Flexibility Provider (IFP), payment to the BRP for the energy curtailed: the “versement”, which was validated by the French constitutional council in 2013
- CRE’s decision of December 2013 opened participation of Ancillary services for DR (FCR and aFRR) which some complementation after years

as Articles L 271-1 to L 271-4 of energy transition law from August 2015 and the 2016-1132 decree.

7.4.1 Implicit DR

Already in 1956 Electricité De France (EDF) applied ToU pricing programs to large industrial customers and to residential customers in 1965. This experience, situates France and especially EDF the leader in ToU pricing programs [41]. Industrial establishments (mining, manufacturing and cold-storage) are the main users of DR in France [10].

France is one of very few countries in Europe where the tariff promotes DR programs based on CPP. In 1993, Electricité De France (EDF) introduced “Tempo” program. In this program the year was divided in three: 300 days of cheaper electricity than ToU, 43 days that electricity has quite higher rates compares to normal ToU and 21 days which are the most expensive [41]. EDF had in 2010 around 350,000 residential customers and more than 100,000 small business customers using the Tempo tariff. Nowadays it is still in use [160]. Other regulated tariffs are called “*Effacement jours de pointe*” which is a CPP as the name in French indicates.

It can be said that France is very developed. Revenues from Self-consumption have been promoted so as self-consumption is very common. They haven’t reached a full smartmeter deployment but they have diverse electricity tariffs available. They are the only country in Europe who has CPP rates.

7.4.2 Explicit DR

France has opened both the ancillary services markets and wholesale market to DR and independent aggregators. In 2013, regulation of the relationship (including roles and responsibilities) between aggregators and retailers/BRPs and a standardized framework entered in force. France is one of only three European Member States (Finland, GB and France) where residential consumers are also engaged to DR. France has started to deploy “new generation” smart meters, which have more frequent measurements permitting consumer participation in balancing markets.

French TSO has adapted its products to facilitate DR and aggregation. However, certain consumers with a curtailment clause in their retailer contract cannot be explicit responsive. Compensating this issue, capacity market enables consumers’ access. Moreover, certification process permits DR operators to go closer to real time than

generators; existing generators need to be certified 3 years ahead whilst DR operators only 1 year ahead of the delivery year, this enables better flexibility provision from.

DR participation to the balancing power market and reserves was implemented for first time only to industrial in 2003, extended to aggregated industrials in 2005, and finally opened to aggregate residential in 2007.

Many issues due to changes have had to be faced. Before 2014, frequency control from generators had a fixed price; RTE wanted the same pricing when opening the market to DR. This was made by the purchase of DR by producers, expecting that they will include them because of lower prices of their generation, but as generators in France are mainly owned by EDF they were overpowering the market. RTE is reviewing the model although aggregators have successfully engaged to a certain extent.

Independent aggregation is permitted and roles and responsibilities have been put in place between the BRP/retailer and aggregator. Customers and aggregators can participate to wholesale day-ahead and intraday markets (*Notification d'Échange de Blocs d'Effacement*, NEBEF), balancing market (mFRR, RR), FCR and aFRR. Since 2014, consumers/aggregators do not need to sign any contract with a BRP/retailer to provide flexibility in balancing markets, NEBEF or Capacity mechanisms. Nevertheless, bilateral contracts between consumers/aggregators and producers are needed for ancillary services, FCR and aFRR participation of DR. These agreements are usually with EDF, who buys and sells most of the resource in the market. This fact again difficult new entrants' penetration but there exist several successful cases.

Ancillary requirements are strict, minimum bid sizes (1MW), contracts for these reserves have to be annual [161] and prices are regulated by the "Code de l'énergie" since 2014. This law states that FCR participation is mandatory for higher power than 40 MW (except RES) and aFRR for larger power generating facilities than 120 MW. The actual result of its application is more than 10 % of French FCR capacity and 2 % of aFRR contracted capacity.

Also, there exist interruptibility programs for large consumers (above 60MW) which are implemented to decrease electricity demand thereof within 5 seconds.

The standardised process between BRPs and aggregators is a significant enabler which includes the definition of the traded volumes of energy, a price formula of the compensation for the transferred energy and data exchange through the TSO provided to the BRP. The price formula of the compensation can also be seen as a barrier because it does not reflect the changes in electricity market prices.

In France, to ensure stay in balance, BRP/retailer pay the *sourcing costs* which is the amount paid when they buy electricity in advance of actual consumption due to consumers' unpredictable consumption patterns. Retailers state that aggregators should pay them for these losses, but there exist some debates between residential and consumer's aggregators.

In 2014, secondary reserve open it access to load participation and also was put in place the NEBEF mechanism which allows access to DR in the wholesale electricity market. The volume negotiated in NEBEF in 2014 was 347 MWh, 1587 MWh in 2015 and around 9000 MWh in 2016.

In explicit DR France is best positioned. All markets are opened and also for aggregation and independent aggregation as well. There are not minimum bid sizes but they need to be symmetrical. Prequalification is only needed at aggregation level and payments and penalties are fair and reasonable.

7.4.3 French pilots

European Regional Development Fund (ERDF) runs 15 demonstration projects in France aiming at testing programmes for Smart grids development. The projects include RES integration, electricity storage, demand response and energy efficiency.

One example in France is Actility. This company has developed "ThingPark Energy" platform using IoT, Data Management and Electricity Markets. The application integrates every phase of DR and load shifting programs providing real-time energy data to utilities and monitors the performance of their portfolio [162].

Energy Pool is an aggregator of mainly large industries which operation started in 2008. They aggregate at least 1000 MW of loads for load reduction. As aggregator it identifies flexibility potential offers it in the balancing markets (day-ahead and intra-day), reserve markets (long-term contracts and emergency operations), and capacity markets (mid-term or long-term contracts). Energy Pool clients receive specific payments for their participation in load management programs [10].

Also, ENR-Pool project by Energy Pool [163] has provided aggregation of 100 MW of DR from industrial loads for participating in ancillary services. Based on the experience of this pilot project, Energy Pool and Schneider Electric have developed a commercial portfolio of 1500 MW of industrial load flexibility, which is active in multiple markets in several countries[111].

Voltadis is an aggregator which customers receive a device for free, called Bluepod, which very simple to be installed and its aim is to reduce heating operations according

to grid needs. The device works automatically and without any additional tariff settlement and if needed and in any moment it can change its working mode to manual. [10].

Another French pilot jointly with Germany is the *Smart Border Initiative* (SBI) project addressed to integrate the electricity grid with the electric mobility, district heating, cooling systems, buildings... It is divided in 3 modules with the aim to develop a cross-border data management system and common standards for optimisation of the electricity distribution, reach a more balanced, interconnected and resilient energy system, define the coordination procedures between the involved parties [164]. In 2017, the project didn't reach a high level of maturity so quantitative societal cost-benefit analysis and impact could not be accurate [165]. Actualized and detailed information can be found in [166].

Flexiciency French demonstration aim is the validation of a use case related to advance monitoring and local control services. The demonstration will highlight the added value of the market place in terms of the opening-up of the electricity retail markets. It is led by the local French DSO (Enedis), a service providers (Joule Assets) and an aggregator (KiwiPower) [167]. In the pilot, a UK aggregator wants to operate on the French market. The aggregator sends a request to the DSO to get data from the zone of interest and the DSO provides it. Aggregator does some simulations which results are sent to the service provider in another country for further economic evaluation [167]

7.5 The Netherlands

As in other Member States, in Netherlands, regulatory barriers remain an explicit DR deployment issue and hinder market growth. These barriers are related to BRP and aggregators regulated roles and responsibilities, independent aggregation is not enabled, which reduces competition around demand side programs (DR is attached to electricity price) and the baseline methodology is made through a bilateral agreement rather than as a standardised and open process.

Tennet, the Dutch TSO, estimates that Dutch market has around 1 GW of flexibility (including generation assets). The annual volume of balancing energy activated by the TSO in 2017 stands at 500 GWh [168].

More information of Dutch electricity markets cannot be provided due to the author knowledge of Dutch. Information regarding DR in English has not been accessible.

7.5.1 Implicit DR

Solar PV for DR is largely used in The Netherlands, with prosumers being defined and regulated in general Energy or Electricity law. The Electricity Act sets out residential prosumers' right to feed self-generated electricity into the grid, for which grid operators must provide a contract to prosumers. Compensation to prosumers is determined by the net metering scheme. Under the net metering scheme, the electricity bill summarises how much electricity the prosumer has produced and the supplier has delivered, respectively, and the prosumer is only invoiced for the difference, i.e. net consumption [169]. This is barrier to face from DR deployment point of view because it reduces load shifting from consumers.

The proposal regarding to compulsory installation of smart meters in small consumers was very strict on a first moment; it could be punished by law with 6 months' imprisonment. For private reasons people complained and the proposal was abolished. Currently end users have the right to refuse a smart meter.

Implicit DR is incorporated in the BRP portfolios, mostly under some kind of structured contract with prosumer of an optimal scheme. Some very large consumers are active on the market themselves. Nevertheless, apart from the known platforms for RTP participation, also to implement RTP, retailer and aggregator can sign a tripartite contract with the consumer to optimise the energy consumption [170].

The Electricity and Gas Acts stated that dynamic tariffs for DR are already implemented [74]. The electricity transmission tariffs are proportional to the voltage of the network to which the customer is connected and the capacity of the connection [171].

Regarding implicit DR, in The Netherlands use of self-consumption is widely spread in spite of the low revenues. In the Netherlands they have wide deployment of smart meters but benefits that could provide aren't used properly due to lack of tariffs available.

7.5.2 Explicit DR

The Netherlands has started to deploy "new generation" smart meters, which are enable consumer participation in balancing markets although the pooled load is measured and pre-qualified to fulfil requirements as an aggregate.

Aggregators' roles are not specifically defined and neither do competition rules among suppliers and the independent aggregator. The controller of Direct load control could be either energy suppliers or the aggregator companies instead of letting TenneT

to be the controller of direct load control, this choice has the advantage of leaving more rooms to the market players, thus increasing market competition.

Intraday and day-ahead markets in the Netherlands are all open for DR. Since liberalisation, every connection on the grid has to be balance responsible, DR and aggregation are allowed in all FRR (Regulating, Reserve and Emergency Power) and in Replacement Reserves which are traded in the intraday market [172].

The most important instigators of DR are the BRPs operating the balancing market. They manage imbalances with their own portfolios and so-called “passive balancing/passive contribution”. This structure is a unique model of balance; it is simpler and prevents third-party aggregators to access consumers directly. It is based on voluntary contributions from BRPs to balance the grid, without being selected via a bidding ladder thanks to publicly available of close to real-time imbalance positions and prices. With that clear and timely price signals model, Tennet has succeeded in flexibility, particularly to green-house owners.

Independent aggregation is not enabled, which reduces DR competition due to its dependence to the electricity price. DR offers can be bided into the wholesale market through the retailers’ supply contract. BRP is the responsible to carry out DR by managing imbalances through real-time dispatch and being able to act as BSP. The consumer has to accept the aggregator/BRP offer or find another retailer to renegotiate the retail contract to access to DR. Aggregators function is to optimise services to BRPs only, through trading on the day-ahead, intraday and balancing markets. Aggregators role can also be carried out by BRPs or BRPs can hire a third-party aggregator but for that last case to be possible, third-party need an agreement with the consumer’s BRP and with its retailer.

Explicit DR has only been visible in the direct activated or incident reserve market (mFRR), that until recently was mainly open for demand. However, TenneT has updated ancillary services product specifications for balancing and processes have been streamlined to allow shorter bid periods (i.e 1 min mFRR instead of normal 5 min bid) [173].

In regard to balancing market and ancillary services, primary control performance is signed weekly based with a symmetrical product which difficult access for DR and aggregation. Minimum contracted bid in Regulation Capacity (aFRR) is 4 MW with annual tender. Reserve Capacity (mFRR), which bids are voluntary, can be for balancing purposes and for other purposes (re-dispatch). Reserves scheme is mandatory to be available for connected parties bigger than 60 MW and voluntary with their own condi-

tions for smaller ones [174]. It is mentionable that minimum contract volume in emergency capacity is high, 20 MW but it allows aggregation, it has to be provided within 15 min., and shall be available nearly 24/7.

To conclude, in The Netherlands all markets are accessible, aggregation is allowed but is not independent aggregation, it should be done under BRP or aggregators. Bidding in primary reserves are not allowed, they do allow in secondary and tertiary reserves with high bids but with not symmetrical requirements. Payments and penalties are fair and reasonable.

7.5.3 Dutch pilots

The consumers are also mostly large industries, greenhouses, or those operating in the petrochemical industries. Some of these aggregators are Powerhouse [175], Energie Data Maatschappij [176], NL Noodvermorgenpool and Agroenergy.

Agroenergy has a platform called *BiedOptimaal Intraday* which communicate intraday prices to consumers and make some recommendations for the best hours for intraday participation among other information [176]. In 2018, this aggregator was activated for emergencies 41 times for durations between 15 minutes and 1.5 hours.

A pilot of Block of Buildings called *Jouw Energie Moment* (your energy moment) is being performed by DSO, Enexis, the energy retailer, Greenchoice and the project developer, Heja. The goal of the project is to test dynamic pricing for household consumers where smart appliances react to day-ahead market prices automatically [177]. The retail tariff depends on the day-ahead price variation, is multiplied by a factor not to exceed the traditional fixed kWh price for electricity from the supplier. Investigators want to see how much residential participants will change their behaviour and the amount of services provided to the grid [178].

As in other countries, Gridflex a three-year microgrid pilot program in Heeten [176]. Participants are provided with a battery as much as if they have PV or not and can control their consumption and generation of energy in real time. The energy is stored, marketed and used locally as much as possible, it is not necessary to buy it. The costs of this energy are settled in the neighbourhood [179].

The PowerMatcher open source software developed by Toegepast Natuurwetenschappelijk Onderzoek (TNO) is a multi-agent coordination system facilitated by the Flexible Power Alliance Network (FAN) that has been developed to provide this kind of coordination. The heart of the system is an electronics market, where local control agents negotiate using strategies based on short-term micro-economics [61].

Mastervolt International, Alliander, Eindhoven University of Technology, Amsterdam Smart City and Green Spread InEnergy are working together in the pilot *Storage integrated Multi-agent controlled Smart Grid (PV SiMS)*. The models develop technology and try to optimise business models regarding energy storage and energy micro-trading investments in small-scale renewables [180]. The goal is to test the value the new supply structure considering the understanding of the prosumer and its relations with the electricity supplier and the grid operator [181].

Blockchain application for managing the electricity grid and maintain the security of supply is carried out by TenneT, Sonnen, Vandebron and IBM. As part of a broader Digital Transformation Programme, with Hyperledger Fabric, Tennenet tries to integrate flexible capacity from electric cars and household batteries into the electrical grid for balancing purposes. Vandebron will provide this service to its customers without compromising the availability of their car battery. The blockchain enables each car to participate by recording their availability and their action in response to signals from TenneT [182].

The overall objective of the FLEXNET (FLEXibility of the power system in the NETHERlands) project was to analyse demand and supply of flexibility in the power system of the Netherlands up to 2050 at both the national and regional level analysing the modifications needed from both demand and supply side and societal concerns and changes [183].

8. CONCLUSIONS

8.1 Answers to the research questions

Conclusions are mainly be covered by answering the research questions proposed at the beginning of the Master Thesis.

How is the legislative framework of DR across Europe?

It is important to emphasize that the policy and design of the market should be based on the necessary requirements to guarantee industrial companies' business, while allowing the value of the flexibility of the demand response. The DR market is underdeveloped in comparison to USA market but is increasing due to the encouragement made by legislations and proposals among the European Member States.

Since 2005, the EC is pushing for the creation of a single energy market to increase security of supply, be more climate friendly, increase market competition and be more responsive. The most important step towards DR implementation was made in 2012 by the Energy Efficiency Directive in which on its Art. 15 encourages DR participation alongside supply in wholesale and retail markets, provide balancing and ancillary services to network operator in a non-discriminatory manner. Also, the development of the Networks Codes intends to harmonize the electricity market in Europe in order to facilitate electricity trade within the EU. These Codes involve DR because the result will introduce a common framework of roles and responsibilities relate to frequency restoration reserves and replacement reserves, balancing imbalances in which DR could participate.

Clean Energy Package from 2016 and the publication in June 2019 of the Electricity Regulation and Electricity Directive are very important milestones for DR deployment. During the next years more initiatives regarding aspects on the Directives should be implemented. Transition is slow, it will last years due cost of changes, lack of awareness by the population and development of regulations all these aspects should evolve in the same pace. In spite of that the European Commission and governments are doing their best to take advantage of DR benefits as soon as possible.

How the introduction of DR affects the reliability of the power grid?

Main efforts for DR are the improvement of the quality of supply, security and reliability of the power system both at the system level and at the individual customers. DR effects can intervene in both levels. Small generation units' aggregation; penetration of bi-directional electricity flow, technology development... allow make some changes in electricity power systems which improve assuring the three main objectives of power systems. Those changes are referred also to increase participants in the chain of energy supply while maintaining the total of consumption or reducing it if consumption used efficiently.

DR actions could balance the grid so improve grid reliability from the consumption side. These actions are the reduction of energy consumption particularly during critical periods (peak clipping), moving the energy consumption from peaks to periods of less consumption (load shifting) or using on-site generated energy for self-consumption during peaks or even support to balance the grid. Introduction of DR could balance the variable renewable energy generation, reduce congestion on distribution networks. For example, an application that reflects its relevance can be in the case of applying the distributed generation with demand management to keep an island stable during a fault in a radial network. Also, countries like France with high dependence on nuclear plants and Finland with large consumption of electric heating are the two countries more interested and developed in DR terms, these countries are good examples of which benefits DR could provide.

DR permit diversify reliability sources applying direct load control, interruptible loads, power based tariffs and using load as capacity resource. More important for reliability and security of the grid is DR participation on ancillary services. Not all Member States have allowed yet all customers/aggregators access to balancing power, reserves and/or ancillary services without discrimination. From the ones that have already implemented it, reliability is assured in cheaper way and has increased competitiveness between parts involved.

Are DR benefits and costs uncertain thereby DR is slowly integrated within competitive electricity markets?

When evaluating demand response, it is necessary to consider it in the context of the entire energy system.

Smart grid structures are opening opportunities for a wide range of companies offering services, hardware and software enabling DR. Benefits and costs do not involve and affect in the same way to the stakeholders, for this reason are difficult to be quanti-

fied. Each consideration is seen differently from each stakeholder viewpoint. TSOs interest to increase competition on balancing power and reserve market is evident everywhere. Cost of reserves/capacity is behind of this development. Everything is related to the desired grade of accomplishment, amount of capacity to provide, region, and existing infrastructure and some benefits for one stakeholder can be seen as a barrier for others, where conflicts of interest start.

As explained in this dissertation, benefits from DR can be economic, operational, planning and environmental. The biggest benefits are firstly for TSOs and secondly for DSOs since they cover all the previous aspects. For consumers the benefit is mainly economic but also the environmental has it repercussion for them because it is the people who suffer the pollution.

From DR operational benefits are remarkable the ability to balance fluctuations with effective ramping. Economic benefits are related to the reduction of the cost of energy, infrastructure costs, and incentives from explicit DR programs and the creation of new business models. Capacity costs are the most uncertain about the benefits that they can provide because are reduced for the system operator but incentives for utilities are also reduced. DR also provides long-term benefits as gaining from capacity planning.

All that benefits have a value in electricity markets. Services provided calls for big investments which can be deferred to all stakeholders and for this reason benefits should include all stakeholders. It is very difficult to value that. After all, for instance BRP and independent aggregators are the most benefited from DR application. Because of that, they should assume more responsibility and be penalised for imbalances when balance cannot be provided and also aggregators non-compliance of their bids.

How DR could interact optimally with energy efficient and climate change actions? Which are the barriers and challenges tackled daytime?

The fight against the climate change depends on the variety of actions that help mitigate it. DR is included in one of these actions with which its use encourages the reduction of greenhouse gases emissions due to the increase in the use of renewable energies and electric vehicles. It should be noted that this is highly related to self-consumption and the electricity storage, two aspects in full swing in the century we live. Effectiveness of DR on climate change and long-term is difficult to establish in a fair way, but it can be assured that increasing of RES which are used for self-consumption and DR reduces GHG emissions and encourage energy efficient use. It also helps to eliminate thermal power plants from the system (but policies play a big role here, i.e Germany).

To avoid delaying more the large deployment of DR there are still several barriers and challenges that need to be faced. Barriers are mainly the lack of awareness and understanding of grid issues and of electricity markets. Also is needed to improve the technology and communications in the energy sector, for instance IoT applications. Moreover the roles and responsibilities of the stakeholders including the allowance of aggregation by law need to be defined to allow easy participation for residential customers. Only a few DR programs are known, available and well used.

There is a necessity of standardize and stablish measures to enable consumers and market parties to offer their flexibility in all markets, ensure transparent and fair payments and compensations, design feasible products further development of the market model and processes for congestion management in cooperation between TSO and DSOs.

How is the current and future overview of the participation of DR in Europe, particularly in five Member States? (Finland, Spain, UK, France and the Netherlands)

Based on the criteria mentioned along the thesis, the current state of DR in the target countries can be summarise in the following tables,

For implicit DR:

IMPLICIT DR	Finland	Spain	UK	France	The Netherlands
Self-consumption	Yes	Yes, recently "sun tax" is eliminated. Connection fees remain	Yes	Yes	Yes
Revenues load shifting/self-consumption	Yes, not high	Very Low	Yes	Yes	Only to CHP plants
Smart meters rollout	Very high	High	High	Medium	Medium-high
Type of tariffs available (how commonly are used is no public available)	ToU RTP	ToU (two or three periods per day) and PVPC	ToU RTP	ToU-Tempo CPP- Effacement jours de pointe	ToU RTP

Table 9. Current state of Implicit DR in target countries

For Explicit DR:

EXPLICIT DR	Finland	Spain	UK	France	The Netherlands
DR access to markets	All markets are accessible	None	Only balancing and capacity market	All markets are accessible	All markets are accessible
Aggregation	Allowed	Not allowed	Allowed	Allowed	Allowed
Service provides access to markets	Role for independent aggregators not defined	None	Lack of clarity relationship between aggregator and retailer	Independent aggregation permitted and standardised processes	Independent aggregation not enabled, under BRP aggregator
Participants requirements	Minimum bid sizes are large but not symmetrical bidding	None	Quite high minimum sizes and symmetrical bidding	Not high minimum sizes bids but symmetrical bidding in 1 ^o and 2 ^o reserves	Primary reserves not allowed and 2 ^o and 3 ^o reserves not symmetrical but high bids
Prequalification payments and penalties	Prequalification at aggregation level, unattractive payments and has some penalties	None	Adequate payments but unequal per MW between supply and demand [12](are not public)	Prequalification at aggregation level. Fair and reasonable payments and penalties	Prequalification at aggregation level. Individual negotiation for payments and pay-as-bid for capacity

Table 10. Current state of Explicit DR in target countries

In tables below are reflected in which criteria Member States should work though and which countries have to follow initiatives done by other Member States. In a near future Clean Package Directives and Regulation will be applied in the National laws and hopefully changes though wide DR deployment will take place.

The author would like to remark further steps needed to do for a fair and clear development of DR. Those are

- Continue harmonizing electricity markets as it has being working last years.
- Reach and equal grade of DR development in all markets of Member States.
- National authorities should consider Clean Energy Package and comply with the proposed regulations and Directives.
- More research and development projects on DR and transparency of them to learn from others, increase competitiveness and accelerate energy transition.
- Support from stakeholders and implementation across Europe.

Can DR be used for Ancillary Services?

The greatest challenge and the most valuable fact from DR are to provide ancillary services. Also more technical requirements and changing some organisation and actions in power systems should be faces. For example, DR could enhance the voltage stability in power systems operating under increased uncertainty, and replace some or even all of the spinning reserves typically supplied by conventional generators.

As explained along the thesis, the main benefits and current applications of Explicit DR are related to ancillary services. Ancillary Services can support to frequency control, reserves and voltage control. Generally among Member States, current applications are used for tertiary control reserves but with the development of new technologies and data management pilots are applicable closer to the actual dispatch, FCR, and aFRR, which have more value.

Clean Package Electricity Directive and Regulation are great steps to allow the access of DR to these services among Member States. DR allowance to have access to markets and aggregation are the first steps to take for further integration in ancillary services.

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